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CURVING PERFORMANCE
ANALYSIS OF FREIGHT CAR TRUCKS

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DSL DYNAMIC SCIENCES LIMITED
St-Laurent, Quebec
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The contents of this report reflect the views of the contractor, and not necessarily the official views or policies of the Transportation Development Centre of Transport Canada.

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17. Abstract

A mathematical model of steady-state curve negotiation was used to simulate experimental curving tests of one conventional and six new concept railway freight car trucks. The report describes the model parameters used to characterize the trucks and test conditions. The experimental results from the Truck Design Optimization Project (TDOP) Phase II tests are compared to the model predictions of lateral wheel/rail forces and wheelset angles of attack. The model was also used to perform parameter sensitivity studies for each truck.

The results from this work show that the model can predict trends in the steady-state curving of a number of freight car trucks for a range of operating conditions, and can be used to determine the influence of parameter variations on truck curving performance.

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17. Résumé

Ce rapport décrit les paramètres de calcul visant, par simulation en régime permanent, à caractériser le comportement dans les courbes de sept bogies de wagons, un de type classique et six de conception originale, et à définir les conditions d'essais devant être représentées par simulation. Il explique comment les données d'expérimentations effectuées dans le cadre du programme TDOP (Truck Design Optimization Programme), phase II, ont été comparées aux données obtenues par simulation des facteurs en jeu; à savoir les forces transversales agissant aux points de contact rail/roue et l'angle d'inscription. Ce même modèle mathématique a servi aussi à étudier la sensibilité aux variations introduites dans les paramètres appliqués.

Il a été constaté que le modèle en régime permanent permet de dégager des tendances générales dans le comportement des bogies étudiés, et ce, dans une gamme définie de conditions d'essais simulées; il permet en outre de déterminer l'effet des variations introduites dans les paramètres appliqués.

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SUMMARY

This report describes a project carried out by DSL Dynamic Sciences Limited, to study the curving performance of freight car trucks using a steady-state mathematical curving model. The objective of the project was to establish the capability of the model to predict the curving behaviour of seven different freight car truck designs by comparing predicted results with measured data from an extensive test program.

The work consisted of the following segments:

- analysis of the truck designs and the test conditions in order to define values of parameters which are used in the model.
- modifications to the model to handle special truck features (e.g.: forced wheelset steering for the Devine-Scales truck).
- simulations to determine the theoretical curving behaviour of the trucks.
- comparisons between theoretical and experimental results.
- simulations to determine the sensitivity of the curving behaviour to various selected parameters.

The results from this work show that the model can predict trends in the steady-state curving of a number of freight car trucks for a range of operating conditions, and can be used to determine the effects of parameter variations.

Recommendations for future work include further validation and enhancement of the model.

RESUME

Description des travaux entrepris par DSL Dynamic Sciences Limited pour étudier le comportement dans les courbes de bogies de wagons, par simulation en régime permanent. Ce programme visait à établir dans quelle mesure il serait possible, grâce au modèle mathématique élaboré, de représenter le comportement de sept différents bogies; la méthode utilisée a été de comparer entre elles les données obtenues par calcul et celles tirées d'expérimentations antérieures.

Les étapes suivies ont été les suivantes:

- déterminer l'ordre de grandeur des paramètres de calcul par l'analyse des caractéristiques générales des bogies et la définition des conditions d'essais à simuler.
- adapter le modèle aux caractéristiques particulières de chaque bogie; par exemple, direction obligée dans le cas du bogie Devine-Scales.
- déterminer par simulation le comportement des bogies dans les courbes.
- comparer les données théoriques aux données réelles.
- déterminer la sensibilité du modèle aux différents paramètres retenus.

Il a été constaté que le modèle en régime permanent permet de dégager des tendances générales dans le comportement des bogies étudiés, et ce, dans une gamme définie de conditions d'essais simulées; il permet en outre de déterminer la sensibilité aux variations introduites dans les paramètres appliqués.

Le rapport conclut en recommandant que, dans les travaux ultérieurs, la validation du modèle ainsi que son amélioration soient poursuivies.

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1. INTRODUCTION

Canada and the United States have been pursuing research in the development of freight car trucks which have improved dynamic performance. One particular aspect is to improve the curving performance of trucks so as to alleviate problems of wheel and rail wear, especially when heavy tonnage trains are used.

As part of Canada's research effort, work had already been done to develop a mathematical model for predicting the curving behaviour of railway vehicles. In the United States, the Federal Railroad Administration (FRA) was sponsoring a research project, TDOP Phase II, to evaluate a number of Type II (premium) freight car trucks on the basis of their performance under representative field conditions. Under the TDC/FRA Joint Research Project Agreement in Freight Car Truck Technology, it was found appropriate for TDC to support an effort by DSL Dynamic Sciences Limited to provide engineering analyses and truck curving simulations to Wyle Laboratories, the prime contractor for TDOP Phase II.

The objective of the work performed by DSL was to establish the capabilities of the mathematical steady-state curving model to predict the curving behaviour of a number of freight car truck designs. The work consisted of performing a number of simulations for seven different freight car trucks and comparing the theoretical results to test data from TDOP Phase II. In addition, a set of parameter sensitivity studies was made for each truck to determine the influence of various parameters on the truck's behaviour.

Chapter 2 of this report gives a technical description of the mathematical model. Chapter 3 describes the work performed, and provides a discussion on the comparison between the theoretical and experimental results. Conclusions and recommendations for future work are given in chapter 4.

2. DESCRIPTION OF THE MODEL

2.1 Introduction

One major problem associated with railway vehicles negotiating curved track is wear of the wheels and rails. To obtain some understanding of this problem, one must determine either analytically or through tests, the behaviour of the vehicle on the curve. In the past, the friction centre method [1, 2] has been used to calculate the forces and the orientation of railway trucks in curves. The method, however, makes many assumptions about the truck and the interaction between the wheel and rail; in particular, the truck frame is assumed rigid, the wheels have cylindrical treads, and some or all the wheels are slipping. As a result, the friction centre method has a limited range of applications. Other authors [3, 4] have used linear models to study the curving behaviour of vehicles. These models, however, are not valid when slip occurs at the wheel or when flange contact is made.

In this project, a nonlinear steady-state curving model of railway vehicles was used by DSL. The model which is described in this section, considers both nonlinearities at the wheel/rail interaction and within the suspension characteristics of the truck.

2.2 Model Definition and Degrees of Freedom

The model represents a rail vehicle which is traversing a smooth section of circular track at a constant speed. The model consists of a half carbody and one truck having two or three wheelsets[1]. This representation using a half vehicle is sufficient for a vehicle having no rotational (i.e. yaw) stiffness between the carbody and truck, since for steady-state conditions, there is no influence on the behaviour of one truck from the other truck.

The truck assembly consists of a rigid frame and conventional railway wheelsets. The wheelsets are connected to the frame by the lateral and longitudinal stiffnesses of the primary suspension at the axle bearings. Figure 1 shows a schematic view of a two axle truck.

A moving orthogonal coordinate system is used whose origin follows the centre of the truck frame and is located along the centreline of the track. The X axis of the system is in the direction of motion of the truck, the Y axis is radially outward from the centre of curvature of the track, and the Z axis is vertical upward.

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[1] The model can be used to represent either two or three axle trucks. However, since TDOP Phase II involved testing of two axle trucks only, for this report discussions on the model shall be limited to the two axle case.

As shown in figure 1, the model has ten degrees of freedom to represent the half vehicle and its two axle truck. The degrees of freedom have the same directions as the coordinate system and are denoted as:

i) q_1 ... lateral displacement of leading wheelset.

ii) q_2 ... longitudinal displacement of leading wheelset.

iii) q_3 ... yaw angular displacement of leading wheelset about the Z axis.

iv) q_4 ... dimensionless rotational velocity of leading wheelset as defined below.

v) q_5 ... lateral displacement of trailing wheelset.

vi) q_6 ... longitudinal displacement of trailing wheelset.

vii) q_7 ... yaw angular displacement of trailing wheelset about the Z axis.

viii) q_8 ... dimensionless rotational velocity of trailing wheelset as defined below.

ix) q_9 ... lateral displacement of truck frame.

x) q_{10} ... yaw angular displacement of truck frame about the Z axis.

The dimensionless wheelset rotation velocities are defined as:

$$q_j = \frac{\omega_i R_{oi}}{\Omega R_c} \quad \begin{array}{l} i = 1,\ j = 4 \text{ for leading wheelset} \\ i = 2,\ j = 8 \text{ for trailing wheelset} \end{array}$$

where: ω_i = angular wheelset rotational velocity about the axle centreline.

R_{oi} = average tread radius of the wheelset when it is in a central position on the track.

Ω = angular velocity of the vehicle as it traverses the curve.

R_c = radius of track curvature.

2.3 List of Assumptions

The following is a list of the basic assumptions which relate to the model. Other assumptions which are of a detailed nature are given in the text.

1. The track is smooth and has constant curvature, gauge and superelevation. In addition, all parameters related to the track such as railhead radius and coefficient of friction are fixed.

2. Conditions of constant forces and moments due to lateral coupler forces, traction, braking, vehicle weight and speed are assumed.

3. There are no dynamic motions in the system, either in the vehicle body, truck frame or wheelsets.

4. The truck frame is rigid. To model a truck having a non-rigid frame, for example a 3-piece truck, an equivalent lateral stiffness is used to represent the parallelogramming stiffness of the truck.

5. The wheels have profiles which consist of a tapered tread and a flange having a conical face.

6. The total creep force between the wheel tread and rail obey Vermeulen and Johnson's formulation for creep force versus creepage [5] . In addition, it is assumed that the gravitational stiffness cancels the spin creep effects.

7. There are only elastic forces (i.e. no frictional forces) in the connections between the wheelsets and truck frame. Also there is no friction between the carbody and truck to prevent truck yaw rotation.

2.4 Features of the Model

2.4.1 Connection between the Vehicle Body and Truck

Figure 2 is an end view of the vehicle body and the truck. As shown in figure 2, forces may be acting on the vehicle body due to gravity, centrifugal acceleration and lateral coupler forces. These vehicle forces impose a net lateral force on the truck frame and a net vertical force on each wheel bearing of the truck. These truck forces are calculated by static force balance and as a result, no degrees of freedom are required for the vehicle body. (The effects of changes in the vertical truck loads due to displacements in the secondary suspension between the truck and body are neglected).

2.4.2 Connections between Wheelsets and Truck Frame

The lateral and longitudinal connections at the primary suspension between the wheelset bearings and truck frame are modelled as sets of piecewise linear force versus deflection segments. The lengths and stiffnesses of the segments are user selectable, and can be used to model different characteristics of the truck. For example, a lateral zone of free play can be specified to study the effects of clearances between the end of the axle and the end of the bearing housing.

2.4.3 Wheel/Rail Interaction

A two point contact representation of the wheel/rail interaction is used in the model and is shown in figure 3. The wheel tread contacts a crowned railhead of a constant radius. Roll of the wheelset about its longitudinal axis is neglected and the point of tread contact is assumed to be in a horizontal plane.

When the flangeway clearance is exceeded, both the tread and flange of the wheel contact the rail. Single point contact of the flange is assumed and is located by two input parameters: e_y and e_z, the lateral and vertical distances between the points of tread and flange contact. The model calculates e_x, the longitudinal advance of the point of flange contact which may result from wheelset yaw and the specific flange geometry. It should be noted that while this longitudinal advance has been previously demonstrated [6, 7] , it is not generally modelled.

This representation of the wheel and rail permits straightforward calculation of the points of wheel/rail contact and does not require the use of either tables of stored values of rolling radii, rolling radii difference, or contact angles, or extensive programs to calculate this data.

The model uses this representation to determine the relative velocities (or creepages) and creep forces acting between the wheel and rail at the points of contact. The wheel/rail forces are shown in figure 4. Appendix I gives a fuller description of these calculations.

2.5 Capability for Modelling Different Truck Configurations

Because the computer program has been written in a modular fashion, it was easily modified in order to study different truck configurations. For this project, three configurations were used:

(i) Rigid frame truck (i.e. having a single piece frame).

(ii) Non-rigid frame truck (i.e. having a three-piece construction with a bolster and two sideframes).

(iii) Rigid frame truck with a forced steering mechanism to the wheelsets.

The RIGID FRAME TRUCK is the program's basic configuration and has been described in sections 2.2 through 2.4 of this report. The Maxiride truck was studied using this configuration.

With respect to steady-state curving, the difference between "rigid frame" and "non-rigid frame" trucks is the mechanism by which the wheelsets can move laterally or (parallelogram) with respect to each other. In a rigid frame truck, this occurs through elastic deformation of the lateral suspension at the bearings. For a NON-RIGID FRAME TRUCK, the bearings of the wheelsets are rigidly restrained by the sideframes and parallelogramming occurs as a result of the yaw flexibility between the truck bolster and the two sideframes. In the program, an equivalent lateral stiffness is used to represent this yaw flexibility. The lateral force balance equations, however, have been modified so that a lateral bolster force (for example, due to superelevation deficiency) is equally shared between the two wheelsets. The majority of the trucks were modelled using the "non-rigid frame" truck configuration (i.e. Type I, DR-1, Barber-Scheffel, Swing Motion, and ACF Fabricated).

The third truck configuration corresponds to that of the Devine-Scales truck which essentially is a RIGID FRAME TRUCK HAVING A WHEELSET STEERING MECHANISM. In this truck, the wheelsets are restrained laterally by the truck frame, and longitudinally by a linkage system connected to the frame and carbody. Whenever the vehicle is on a curve, the linkage tends to force the wheelsets into a radial position. In the model, the mechanism is represented by three distance and two stiffness parameters which define the geometry and flexibility of the linkage.

The program also includes a direct inter-axle lateral stiffness parameter, which is applicable to any of the truck configurations. This feature was used to model the steering arms for the DR-1 truck, and the cross-anchors for the Barber-Scheffel truck.

2.6 Input Data

The input parameters for the model can be classified as being in one of the following four groups:

i) VEHICLE PARAMETERS, describing the vehicle body geometry and forces imposed on the truck as a result of the vehicle weight.

ii) TRUCK PARAMETERS, which consist of primary suspension and truck stiffnesses, clearances within these stiffnesses, truck dimensions and geometric tramming errors.

iii) WHEEL/RAIL PARAMETERS, consisting of all items related to the track, wheel geometry and adhesion characteristics.

iv) OPERATIONAL PARAMETERS, describing external conditions such as speed, traction, braking, track curvature and superelevation, lateral coupler forces.

A sample list of input parameters representing a standard three-piece (type I) 100 ton freight car truck and a loaded hopper car is shown in Appendix I.

2.7 Output Data

For this project, two forms of output were used. The first was a short list which summarized the behaviour of the truck in terms of three measures of curving performance for each wheelset, namely:

i) L ... lateral wheel/rail force of the outer wheel of the wheelset.

ii) L/V ... the ratio of the lateral-to-vertical forces on the outer wheel.

iii) Θ ... the angle of attack of the wheelset with respect to the radial line through the centre of track curvature.

The second form of output was a full list of all the wheel/rail creepages, forces and their components, all the elastic forces and moments between the truck frame and wheelsets, and various displacements associated with the degrees of freedom of the truck.

The short list of output was generally selected for this project, as it contained the same type of results as produced during the TDOP Phase II tests. The second list was occasionally used to provide technical explanations of the behaviour of the trucks, and to check the modifications made to the program.

Samples of the short and long lists of output are given in Appendix I, and correspond to simulations using the sample list of input parameters in the same appendix.

3. RESULTS OF CURVING PERFORMANCE ANALYSES

3.1 Introduction

The work for this project was carried out in two stages. The first stage was to simulate the experimental curving tests of a conventional North American three-piece freight car truck, designated as a Type I truck. In the second stage, six truck designs designated as Type II trucks were simulated to determine their curving behaviour. The results predicted by the model were then compared to those measured in the tests. In addition, a number of parameter sensitivity studies were conducted. At the end of each stage, an interim report was prepared. These are included as Appendices II and III of this report.

This chapter contains extracts from these two interim reports, and summarizes (i) the selection of the model parameters, (ii) the comparison of the results between the model and the tests, and (iii) the results from the parameter sensitivity studies. At the end of this chapter, a discussion is given on the comparison between the predicted curving performances and those measured in the tests.

3.2 Overview of the Experimental Tests

The experimental tests were performed on the following Types I and II trucks:

TYPE I:

(i) ACF Ride Control truck (100 ton)

TYPE II:

(i) Dresser DR-1 truck

(ii) Barber-Scheffel truck

(iii) Devine-Scales truck

(iv) Maxiride 100 truck

(v) National Swing Motion truck

(vi) ACF Fabricated truck

The type I truck was tested using wheelsets having standard AAR 1/20 wheel profiles. For the Type II trucks, wheelsets with CN Heumann profiles were used. The tests consisted of instrumenting each truck and installing them separately under a 100 ton hopper car. The trucks and car were then run over a test section of curved track in empty as well as loaded conditions. The test track contained 9 curves having curvatures varying between 2.5 and 6.2 degrees, and superelevations from 3.22 to 5.08 inches. Runs were conducted at three different speeds for each type of truck, which provided data corresponding to running below, near, and above the balance speed of each curve. Data from the instrumentation was analyzed for each curve to give mean values of the following items:

- lateral wheel/rail force
- wheel L/V ratio
- angle of attack

A detailed description of the test results is given in [8] .

3.3 Selection of Model Parameters

The following section briefly describes the model parameters used for the simulation runs of the Type I and II trucks. The values of these parameters were selected using information supplied by Wyle Laboratories; for example, weight of the vehicle, dimensions of the trucks, and track geometry. There were, however, many parameters for which no data was available. They related mostly to the truck stiffnesses and to details of the wheel/rail interaction, in which case engineering estimates were made for their values. For a more detailed description of the model parameters, and in particular, the Type II truck parameters, refer to sections 2.3 and 2.4 of Appendix II, and sections 3.1 through 3.3 of Appendix III.

— Vehicle Parameters —

The vehicle parameters were selected to represent a 100 ton hopper car, loaded as well as empty, and were the same for all the trucks studied.

— Wheel/Rail Parameters —

The wheel/rail parameters were identical for all the Type II trucks, and correspond to wheels having a CN Heumann profile in nominal new condition, running on a sample curve-worn rail head [9]. Flangeway clearances were based on nominal AAR wheelset mounting dimensions and the measured average track gauge. The wheels were assumed to have equal rolling radii.

Since the experimental tests on the Type I truck were conducted with standard AAR 1/20 wheel profile, the wheel/rail parameters for the Type I truck simulations were selected to represent the standard profile.

— Truck Parameters —

There are basically two types of truck parameters, which relate to the geometry or the stiffnesses of the truck. Values for the geometry parameters (e.g. wheelbase, clearances) were obtained from data supplied by Wyle Laboratories, and are considered to accurately represent the trucks. There was however no data available on the actual stiffnesses of the trucks which were used in the tests. Estimates of their values were made and are summarized in Table 1.

— Operational Parameters —

The operational parameters were selected to represent the curve and speed conditions of the experimental tests. For the Type I truck six curves were selected, whereas for the Type II trucks four curves were simulated, corresponding to those curves for which test data was supplied. The speeds used in the simulations represent the operation of the vehicle at the balance speed, 7 mph above, and 10 mph below the balance speed of each curve. These speeds correspond to the intended vehicle test speeds for the TDOP tests. A list of the curves and their ranges of speeds is given in Table 2.

3.4 Comparisons of Theoretical and Experimental Curving Performance

3.4.1 Direct Comparison of Results

Direct comparisons of the lateral force at the outer leading wheel were made for both Type I and Type II trucks, and of the angles of attack of the leading wheelset on Type II trucks.

In general, the predicted lateral forces and angles of attack for all trucks were found to be lower than those measured in the tests. The agreement between theoretical and experimental lateral forces was generally best on smaller degrees of curvature and for empty vehicle conditions. Figures 5 and 6 show sample graphs comparing the theoretical and experimental lateral forces versus degree of track curvature for the Type I truck and one Type II truck at the balance speed of the curve. Graphs for the other Type II trucks are found in Figures 4.1, 4.2, 4.4, and 4.5 in Appendix III.

The experimental values for the angle of attack did not generally show good agreement with the simulation results. Whereas the simulations showed small and nearly linear variations of the angle of attack with speed, there were often large variations and scatter in the experimental data.

3.4.2 Comparative Ranking of Trucks

A comparison between the simulation and test data was made with respect to the relative ranking of the truck in terms of producing low lateral forces. Figures 7 and 8 show the graphs of the theoretical and experimental lateral forces versus curvature for the Type II trucks in loaded condition at the balance speed. In figure 7, the theoretical lateral force for the Type I truck with CN Heumann profiles has also been included to show how it compares with the Type II trucks. (The experimental data for the Type I truck is not shown, as this truck was tested with standard AAR 1/20 profiles).

The two sets of results are in good agreement and show the same order of ranking of the trucks except for the reversal in rank between the DR-1 and Barber-Scheffel trucks. Also, they both indicate that steering-type trucks (i.e. DR-1, Barber-Scheffel, and Devine-Scales) produce lower lateral forces than non-steering trucks (i.e. Swing Motion, ACF, Maxiride and Type I).

3.4.3 Comparison of Trends

Comparisons were also made in terms of the sensitivity of the lateral force with variations in track curvature and vehicle speeds. No comparisons were made for the sensitivities of the angle of attack due to the large scatter in the experimental data.

— Effect of Track Curvature —

The theoretical results showed that for the range of curvatures studied, there was a nearly linear relationship between the lateral force and curvature at a given load and speed condition. By doing a linear fit on the experimental and theoretical data, the sensitivity of the lateral force (given in units of "lbs/degree") was determined. Table 3 shows comparisons of the sensitivities for six trucks in loaded and empty conditions (the ACF truck was not included as no test data was available). There is reasonably good agreement in the sensitivities for all trucks. Both results show an increasing lateral force with curvature, and a higher sensitivity for the loaded than empty vehicle.

— Effect of Vehicle Speed: Type II Trucks —

The theoretical results for Type II trucks showed that the lateral force increased linearly with changes in speed for a given degree of curvature and vehicle weight. Assuming a linear relationship, the slopes or sensitivities of the lateral force versus speed (in units of "lbs/mph"), were calculated for the theoretical and experimental data and compared at various degrees of curvature.

Generally it was found that there was closer agreement in the predicted sensitivities at the lower degrees of curvature and for the empty vehicle conditions. The theoretical results show a gradual increase in the sensitivity over the range of track curvature, whereas the test data show much larger sensitivities, particularly for loaded vehicles on the higher track curvatures. An example of these comparisons is shown in figure 9 for the DR-1 truck. Comparisons for the other Type II trucks are given in figures 4.9 through 4.12 in Appendix III.

The theoretical and experimental sensitivities of the lateral force-versus-speed for the five Type II trucks (excluding ACF) were then compared for the 5.1° curve. As shown in table 4, the theoretical sensitivities are nearly the same for the five trucks for a given load condition. Allowing for a margin of experimental scatter, the test data also seems to show this phenomenon. Since the weight of the vehicle, the wheel profile, and wheelbase are nearly the same for all trucks, both sets of data indicate that the sensitivity of the lateral wheel/rail force to variations in speed is governed primarily by centrifugal acceleration effects, and not by truck stiffnesses.

— Effect of Vehicle Speed: Type I Truck —

Since there was more test data available for the Type I truck, the sensitivity comparison was made using a statistical analysis. Superelevation deficiency which combines vehicle speed, curvature and superelevation of the track, was selected as the independent variable. The theoretical and experimental values of the lateral force at the leading outer wheel were normalized and plotted as a function of superelevation deficiency The least-square fit of the resultant data was calculated and is shown in figure 10.

Although there was a large scatter in the experimental data, a comparison of the slope of the least-square fit to the slope of the theoretical line shows good agreement between the theoretical and test results.

3.5 Parameter Sensitivity Studies

As the actual values of many parameters during the tests were not known and had to be estimated, a set of parameter sensitivity studies was made for each truck to determine the influence of various parameters on the truck's curving performance. The parameters which were studied generally related to:

(i) stiffnesses of the trucks

(ii) travels and clearances of the trucks

(iii) the coefficient of friction between the wheel and rail

Also, for the Scales truck, the effect of having a modified steering link geometry tending to oversteer or understeer the wheelsets was investigated. In addition, for the Type I truck, conditions of diameter mismatch between the outer and inner wheels and changes in wheel profile (i.e. from a standard AAR 1/20 to a CN Modified Heumann profile) were studied.

The parameters in most cases were varied above and below the baseline values used in the simulation runs for the comparisons between the model and tests, as discussed in section 3.3. A summary of the effects of these parameter variations is given in tables 5 through 7. For a more detailed description of these effects, the reader should refer to sections 5.0 of Appendices II and III.

It is important to note that the trends shown in the tables were drawn from examinations of the results on the 6.2° curve and at the balance speed only. It is possible that the trends may be different for other degrees of track curvature, superelevation deficiencies, or wheel profiles. Exceptions to this are for the studies of wheel diameter mismatch, wheel profile, and coefficient of friction for the Type I truck. In these cases, the simulation data for curvatures ranging from 2.5° to 6.2° were examined.

The following sections describe some of the more interesting results from the parameter sensitivity studies.

3.5.1 Wheel Profile

A study was made to show the influence of standard AAR 1/20 and CN Heumann wheel profiles on the curving behaviour of Type I trucks at the balance speed. Figure 11 shows the results of the lateral force at the leading and trailing outer wheels at various degrees of curvature. It was found that the lateral force for the leading outer wheel was somewhat lower (in the neighbourhood of 5 to 14%) for the CN Heumann profile for the same set of operating conditions.

More significant, however, was the effect of the CN profile on the trailing wheelset. Its lateral force at balance speed is nearly zero for all values of curvature studied. The standard profile, however, produces relatively high lateral forces on the trailing outer wheel for curvatures greater than five degrees.

3.5.2 Wheel Diameter Mismatch

Simulation runs were made for five conditions of wheel diameter mismatch between the inner and outer wheels of the wheelsets for the Type I truck. The conditions ranged from the outer wheels being 3 tape sizes (i.e. 0.060 inches) larger in radius than the inner wheels, to being 3 tape sizes smaller.

As shown in figure 12, wheel diameter mismatch can have a large effect on the lateral forces between the wheel and rail. This is particularly noticeable for the leading outer wheel at the lower degrees of curvature. Positive values of wheel mismatch (i.e. where the outer wheels are larger than the inner wheels) improve the ability of the wheelset to radially negotiate itself around the curve, and hence produce lower lateral forces. Negative values of mismatch, on the other hand, tend to steer the wheelsets away from the centre of curvature of the track which produce higher lateral forces.

3.5.3 Longitudinal Stiffness

Varying the longitudinal pad stiffness of the DR-1 truck has a significant effect on its curving behaviour. This is because the longitudinal stiffness resists the steering action of the wheelsets to align themselves radially with the curve. As seen in figure 13, decreasing this stiffness causes large reductions in both the angle of attack and the lateral force of the leading wheelset.

Another method of reducing the longitudinal stiffness is to add free clearances between the bearing housings and the pedestals of the truck frame. As shown in figure 14, an increase of 3/64" longitudinal clearance for the Maxiride truck on the 6.2° curve reduces the lateral force by 1200 lb (or 15%).

3.5.4 Over-and-Under Steering in the Devine-Scales Truck

On the Devine-Scales truck, the location of the axle link connection to the steering link was varied to study the effects of changing the linkage geometry from the ideal steering configuration. Three values were selected:

1.50"	....	understeered
1.747"	....	ideal steering (baseline)
2.00"	....	oversteered

As shown in figure 15, this parameter has a large influence on the truck's curving performance, particularly for the leading wheelset. The 2.00" link position causes the leading wheelset to have a negative angle of attack (that is, rolling towards the low rail of the curve) and decreases its lateral force. The 1.50" position increases both the angle of attack and the lateral force of the leading wheelset. The opposite effects occur on the trailing wheelset, but to a much smaller degree.

3.6 Discussion of Results

In comparing the theoretical and experimental values of the lateral force, good agreement was achieved in the relative ranking of the trucks and in the sensitivities with respect to curvature and speed. However, in the direct comparison of the magnitudes of the lateral forces, the simulation results were in general lower than the TDOP test data. Reasons for these differences may be attributed to:

1. The truck stiffness parameters were unknown and had to be estimated. However, as shown in sensitivity studies, truck stiffnesses for many of the trucks did not have a large influence on the curving performance, and it is unlikely that the errors in the values of truck stiffnesses are significant in explaining the differences between the experimental and theoretical lateral forces.

2. The wheel/rail geometry parameters were also unknown and hence were estimated. In addition, the estimated coefficient of adhesion was probably too low for the dry desert conditions experienced during the tests. These parameters have a strong influence on the lateral forces.

3. The test data showed that the trucks behaved differently on left as compared to right hand curves. This indicates that there was some asymmetry in the trucks, the source of which is not known. This asymmetry was not considered in the selection of the model parameters, and may have some impact on the mean value of lateral forces for left and right hand curves.

4. There are also inaccuracies in the measured data which involve the test instrumentation and data processing. We do not have sufficient information to make an assessment of this source of error.

A closer correspondence between the theoretical and experimental results could be achieved through adjustment to the values of the unknown parameters. However, due to the large number of these parameters, the matching of results done in such a manner is of questionable value. It would remain a matter of judgement as to whether or not the adjusted parameters could be considered as representative of the actual test conditions. Hence no additional simulations were performed to improve the matching.

4. CONCLUSIONS AND RECOMMENDATIONS

In this project a comparative analysis was made between the predicted curving behaviour of seven freight car trucks as determined from simulations using the steady-state curving model and the behaviour as measured in the TDOP tests. The model was also used in the analysis of parameter sensitivity. The specific conclusions from these analyses are:

1. The model can predict trends in the steady-state curving behaviour of rail vehicles, and can provide explanations for these trends. In particular, the model confirmed the test results which showed that steering trucks produce lower lateral forces as compared to non-steering trucks.

2. The model can be used to study various configurations of railway trucks under a wide range of operating conditions such as track curvature, superelevation, and vehicle speed.

3. The model can complement experimental testing of rail vehicles. Firstly, it can predict results which are either difficult or impractical to measure experimentally; for example: angles of attack and flange forces. Secondly, it can be used to determine the performance of vehicles for conditions which have not been tested. A specific example is the comparison of the Type I and Type II trucks. The experimental results for the two could not be compared because different wheel profiles were used in the tests. However, the comparison was possible and was done using the theoretical model.

4. The model can demonstrate the effects of variations in parameter values on curving performance. This can be useful in the evaluation of new designs of rail vehicle trucks, or in modifications to existing designs.

As a result of this project, the following recommendations for future work are made:

1. Further validation of the model against controlled experiments of steady-state curving of rail vehicles is desirable. In these tests, all items relating to the input parameters of the model should either be controlled or at least measured. In addition, instrumented wheelsets capable of measuring lateral, vertical, and longitudinal wheel/rail forces should be used.

2. Due to the importance of the wheel/rail contact parameters on the curving behaviour of rail vehicles, a study should be performed to compare the present characterization of the wheel/rail contact and other methods, with wheel and rail profiles which exist in railway service. As part of the study, accurate measurements of wheel and rail profiles would be required.

3. Finally, modifications should be made to further enhance the capabilities and realism of the model. Items for consideration include:

   - Improvements to the wheel/rail interaction model; for example, add spin creep and gravitational stiffness effects to the existing model. Other methods of characterizing the contact geometry, as discussed in the second recommendation, might also be implemented.

   - Inclusion of the lateral flexibility of the track due to ties and ballast.

   - Improvement of the truck frame model to allow direct representation of trucks having three-piece frame constructions (without using equivalent stiffnesses).

   - Addition of reaction forces to represent the single shoe brake rigging which is found on most North American rail equipment.

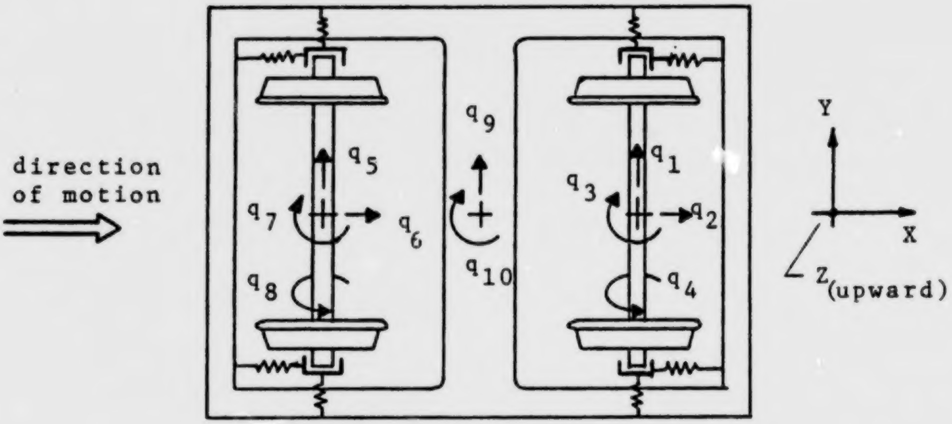

direction of motion
q_9
q_5
q_1
q_3
q_7
q_6
q_2
q_{10}
q_8
q_4
Y
X
Z(upward)

FIGURE 1 - SCHEMATIC DIAGRAM OF THE 2-AXLE TRUCK AND ITS DEGREES OF FREEDOM

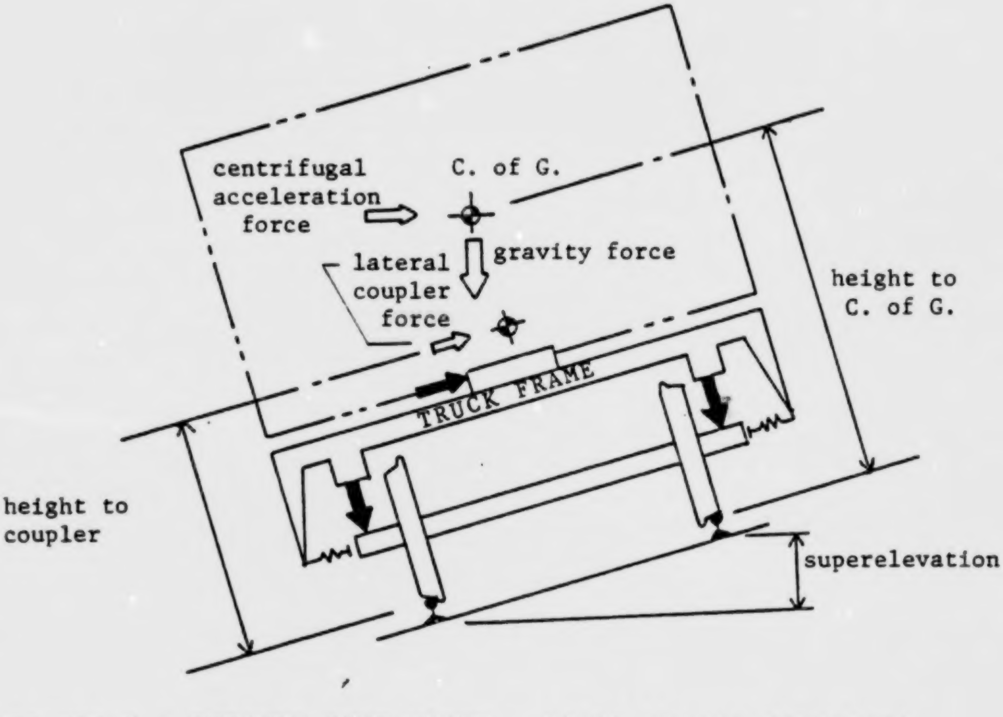

centrifugal acceleration force
C. of G.
gravity force
lateral coupler force
height to C. of G.
TRUCK FRAME
height to coupler
superelevation

FIGURE 2 - VEHICLE BODY MODEL: Light arrows represent forces acting on the vehicle body. Dark arrows are equivalent forces on the truck.

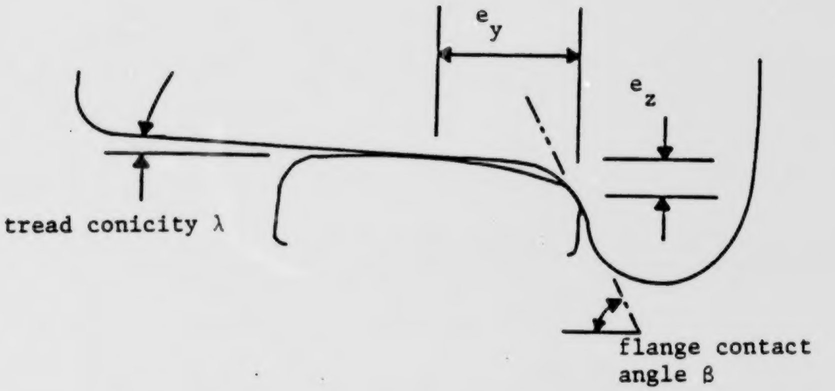

e_y
e_z
tread conicity λ
flange contact angle β

FIGURE 3 - PARAMETERS OF THE WHEEL/RAIL CONTACT GEOMETRY

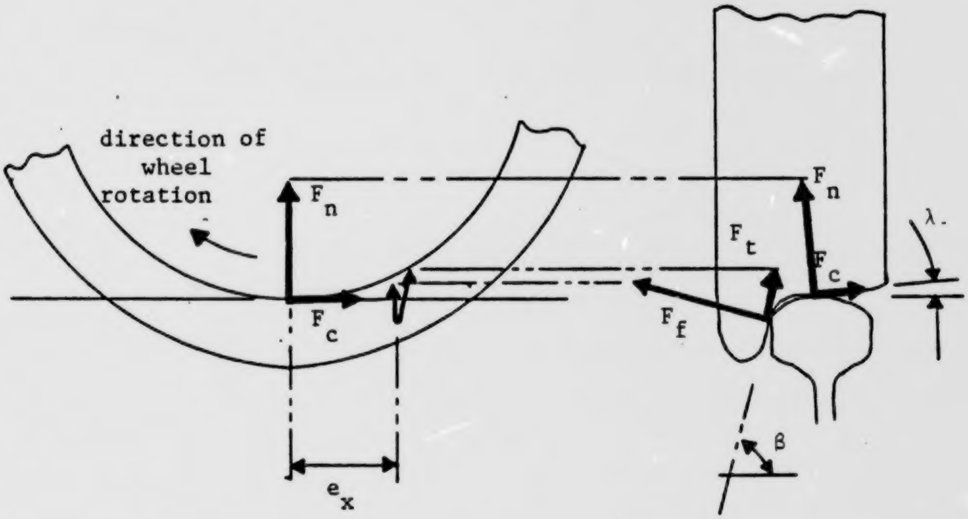

direction of wheel rotation
F_n
F_c
F_n
F_t
F_c
F_f
λ
β
e_x

FIGURE 4 - WHEEL/RAIL CONTACT FORCES:

F_n = tread normal force　　F_f = flange normal force

F_c = tread creep force　　F_t = flange tangential force

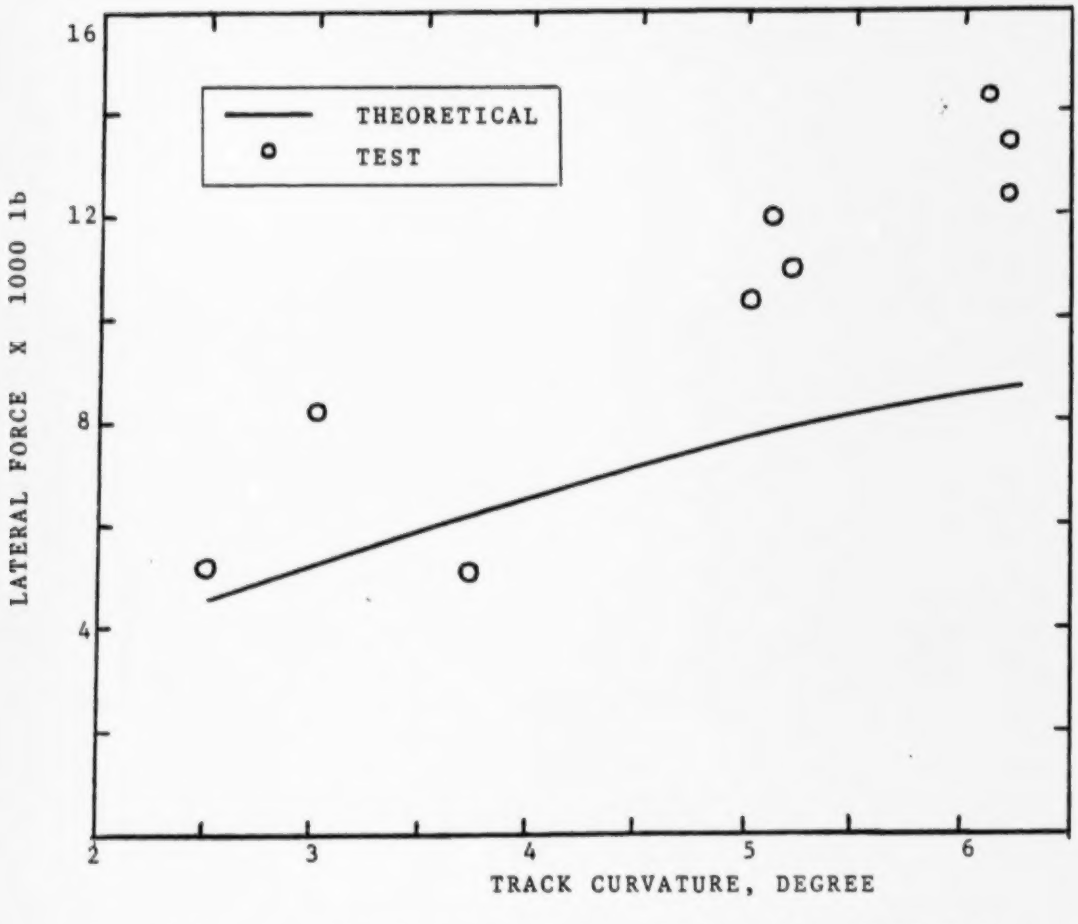


FIGURE 5 - COMPARISON OF LATERAL FORCE VERSUS CURVATURE: TYPE I TRUCK

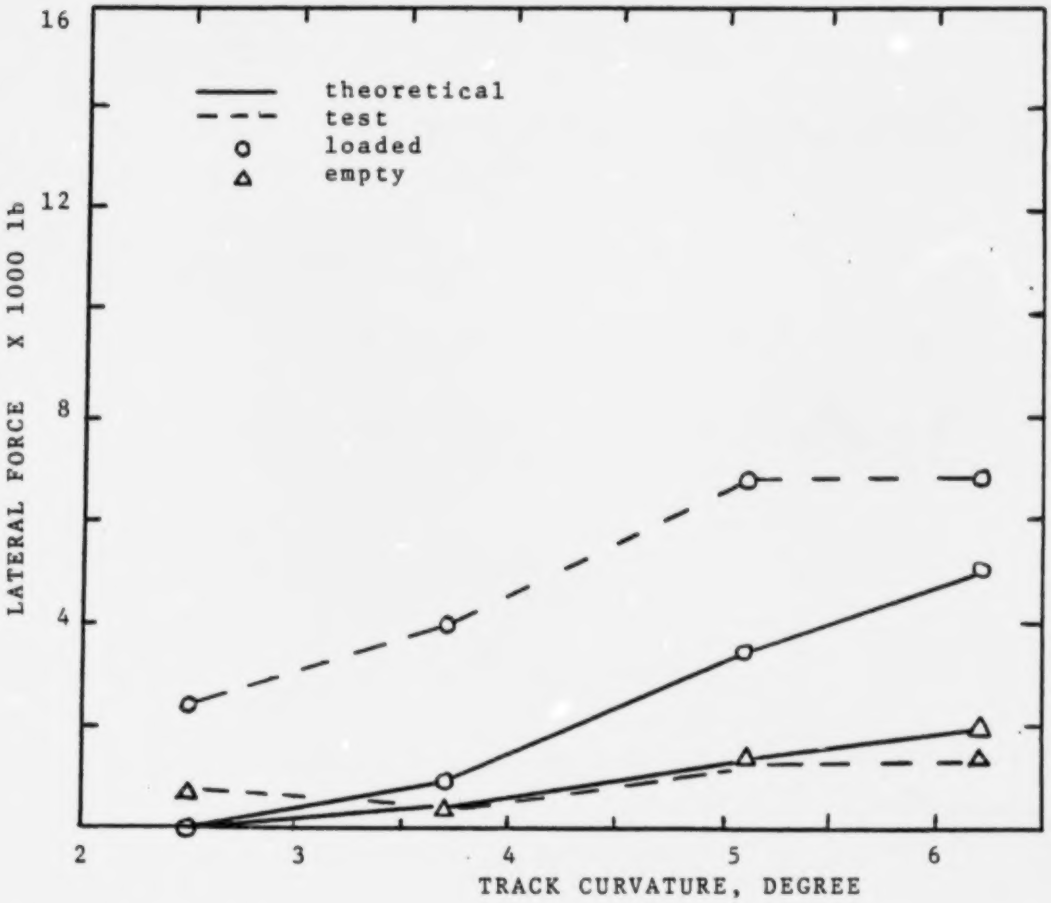


FIGURE 6 - COMPARISON OF LATERAL FORCE VERSUS CURVATURE:
DEVINE-SCALES TRUCK

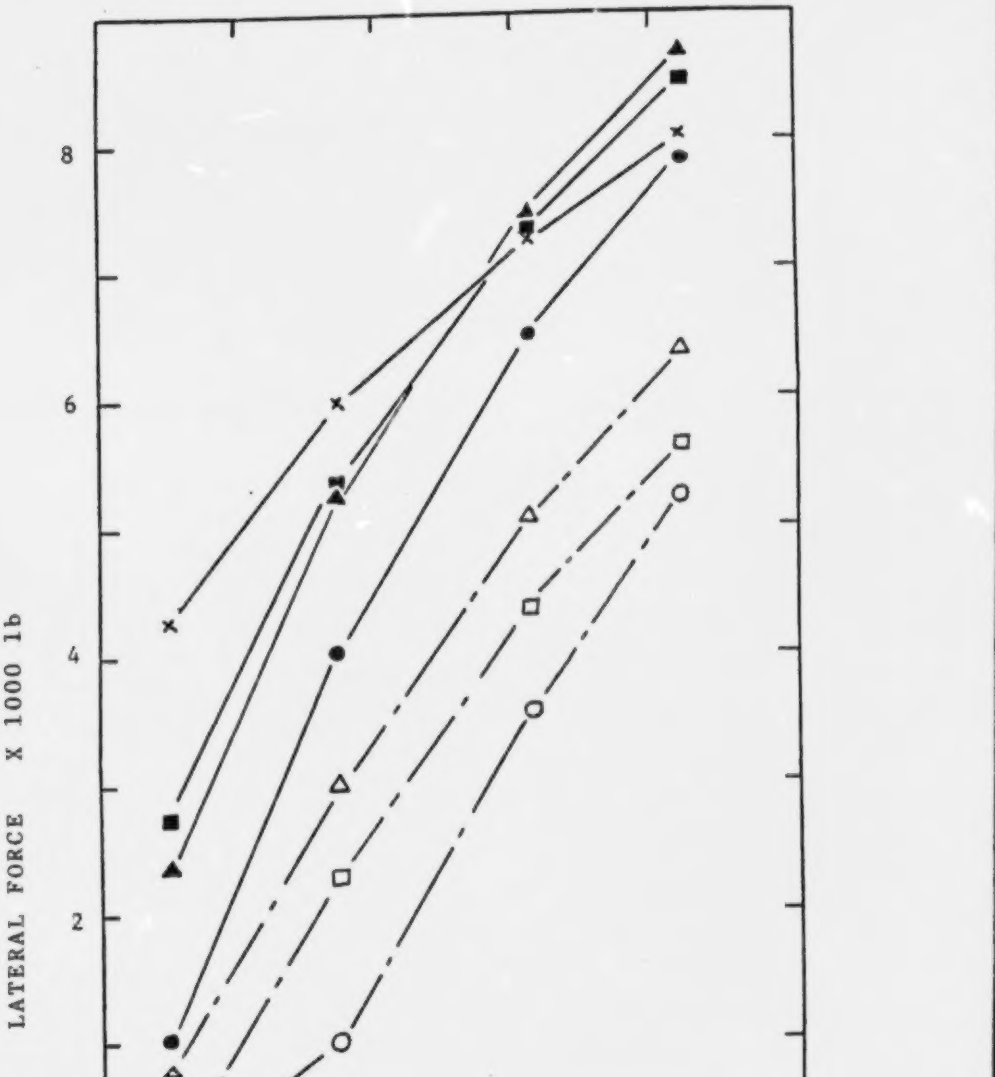


FIGURE 7 - COMPARISON OF THEORETICAL LATERAL FORCE VERSUS CURVATURE: TYPE I AND II TRUCKS, LOADED CONDITION, BALANCE SPEED

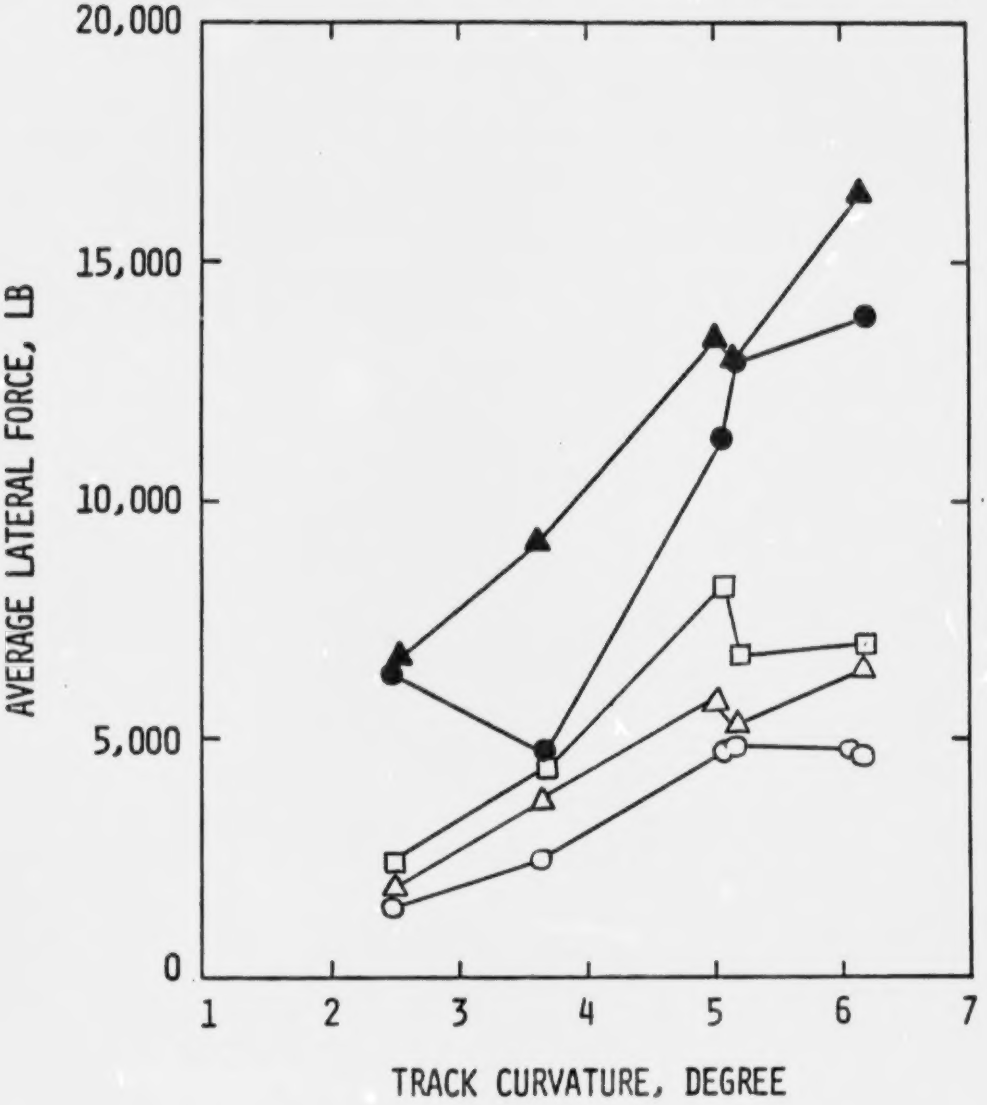


FIGURE 8 - COMPARISON OF EXPERIMENTAL LATERAL FORCE VERSUS CURVATURE: TYPE II TRUCKS, LOADED CONDITION, BALANCE SPEED
(for definition of symbols, see fig. 7)

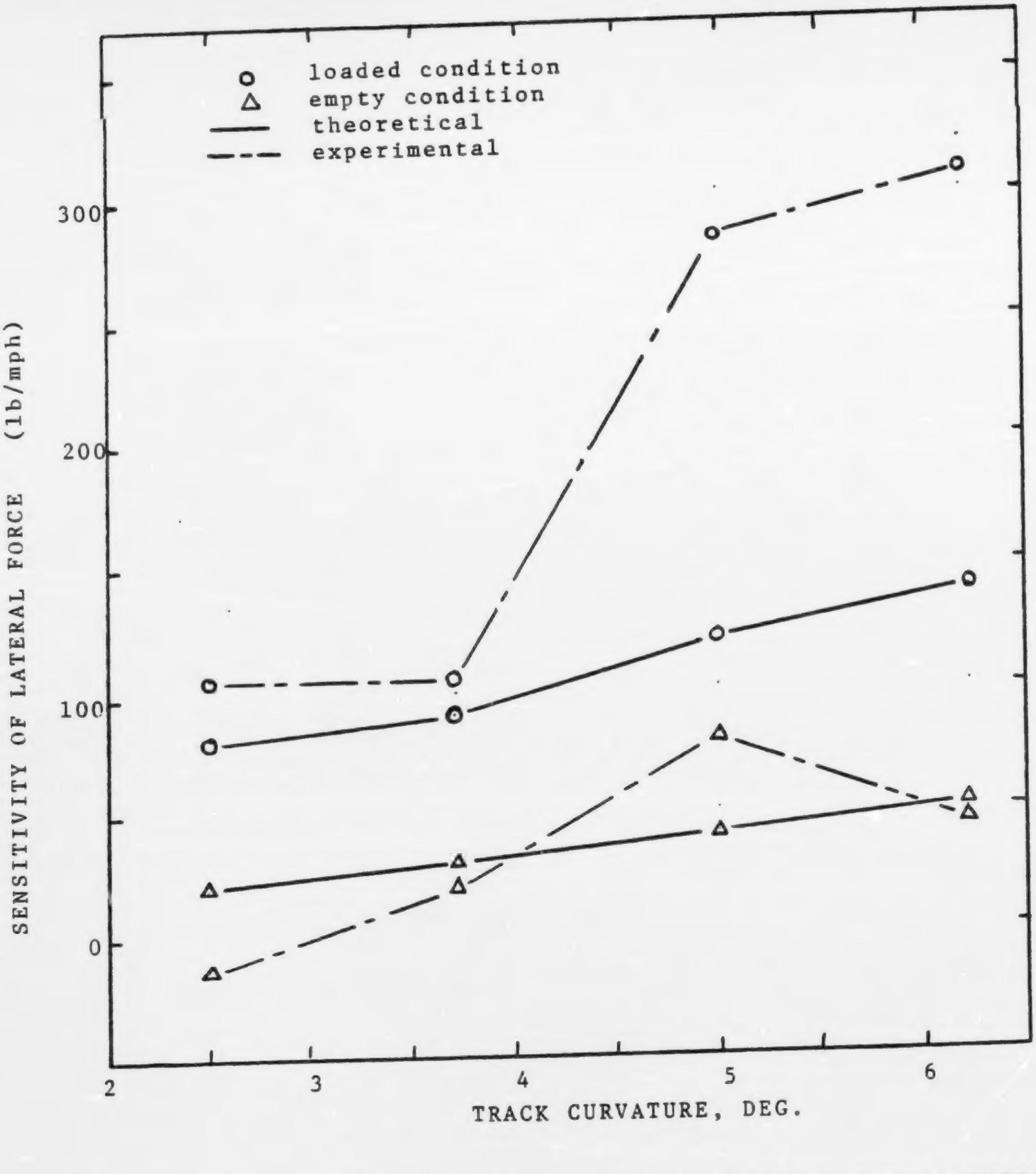


FIGURE 9 - COMPARISON OF SENSITIVITY OF LATERAL FORCE VERSUS SPEED AT FOUR CURVATURES: DR-1 TRUCK

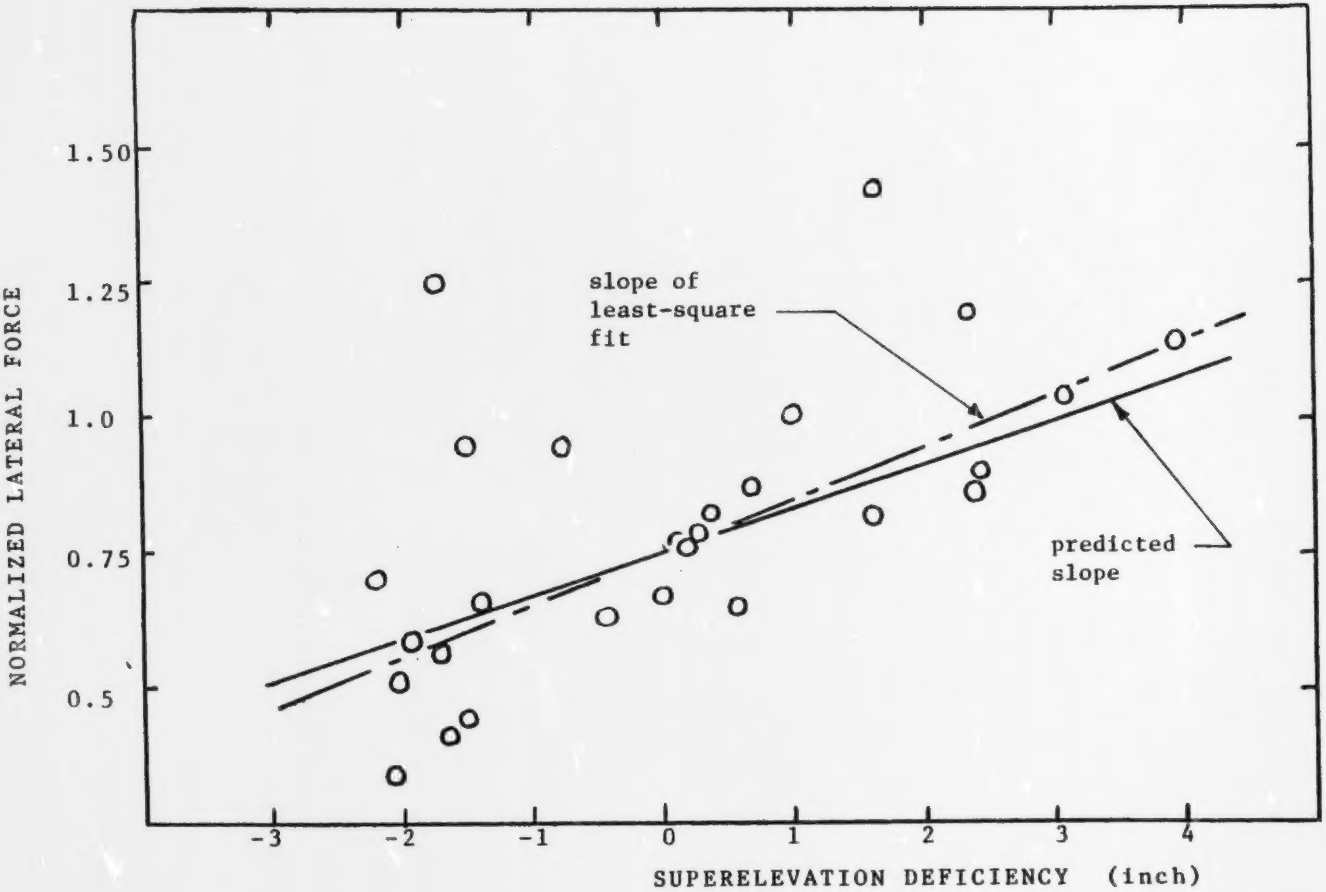


FIGURE 10 - COMPARISON OF NORMALIZED LATERAL FORCE VERSUS SUPERELEVATION DEFICIENCY - TYPE I TRUCK: dots indicate experimental data.

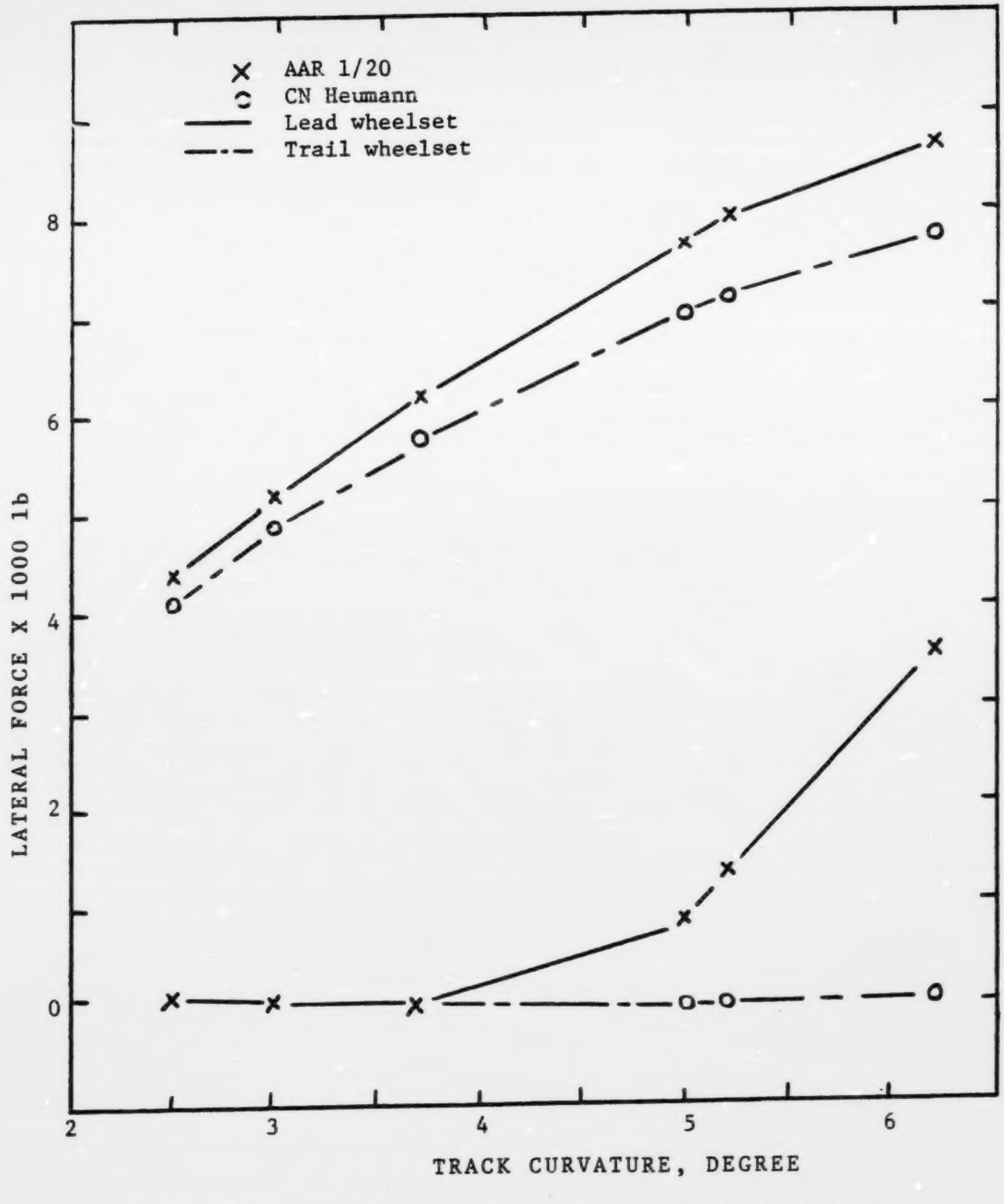


FIGURE 11 - EFFECT OF WHEEL PROFILE ON LATERAL FORCE - TYPE I TRUCK: BALANCE SPEED

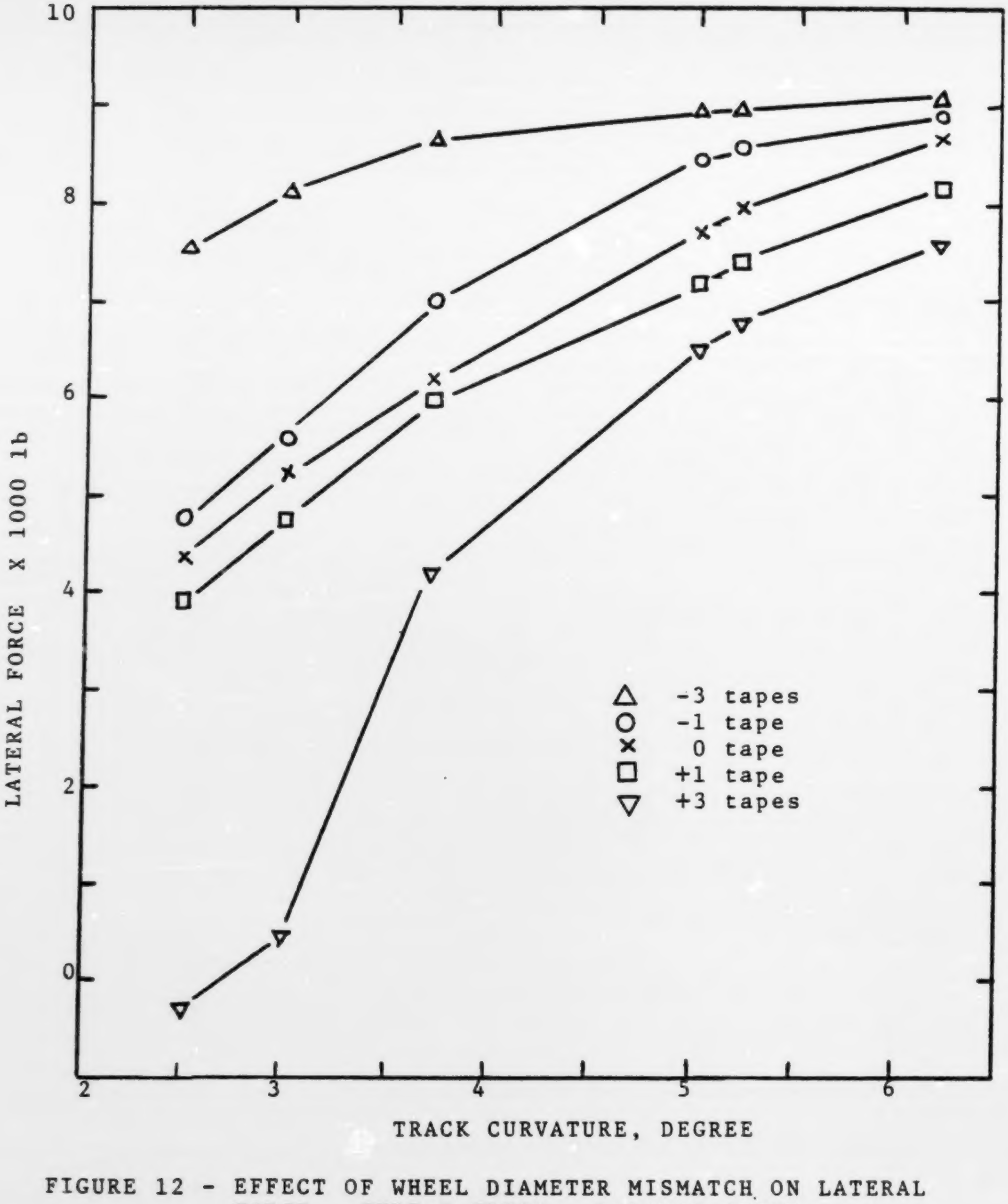


FIGURE 12 - EFFECT OF WHEEL DIAMETER MISMATCH ON LATERAL FORCE - TYPE I TRUCK: BALANCE SPEED

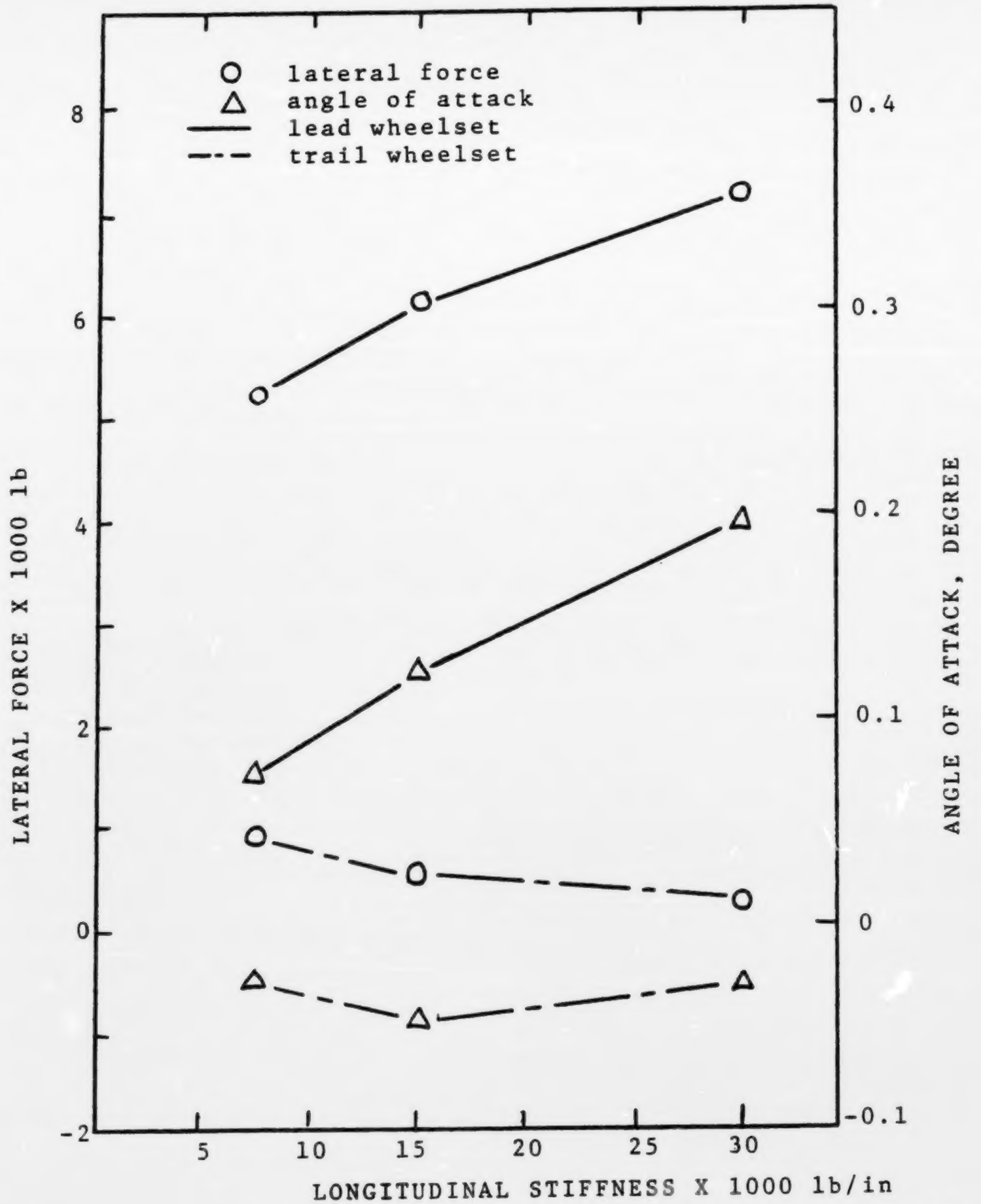


FIGURE 13 - EFFECT OF LONGITUDINAL PAD STIFFNESS ON LATERAL FORCE AND ANGLE OF ATTACK: DR-1 TRUCK, 6.2° CURVE, BALANCE SPEED

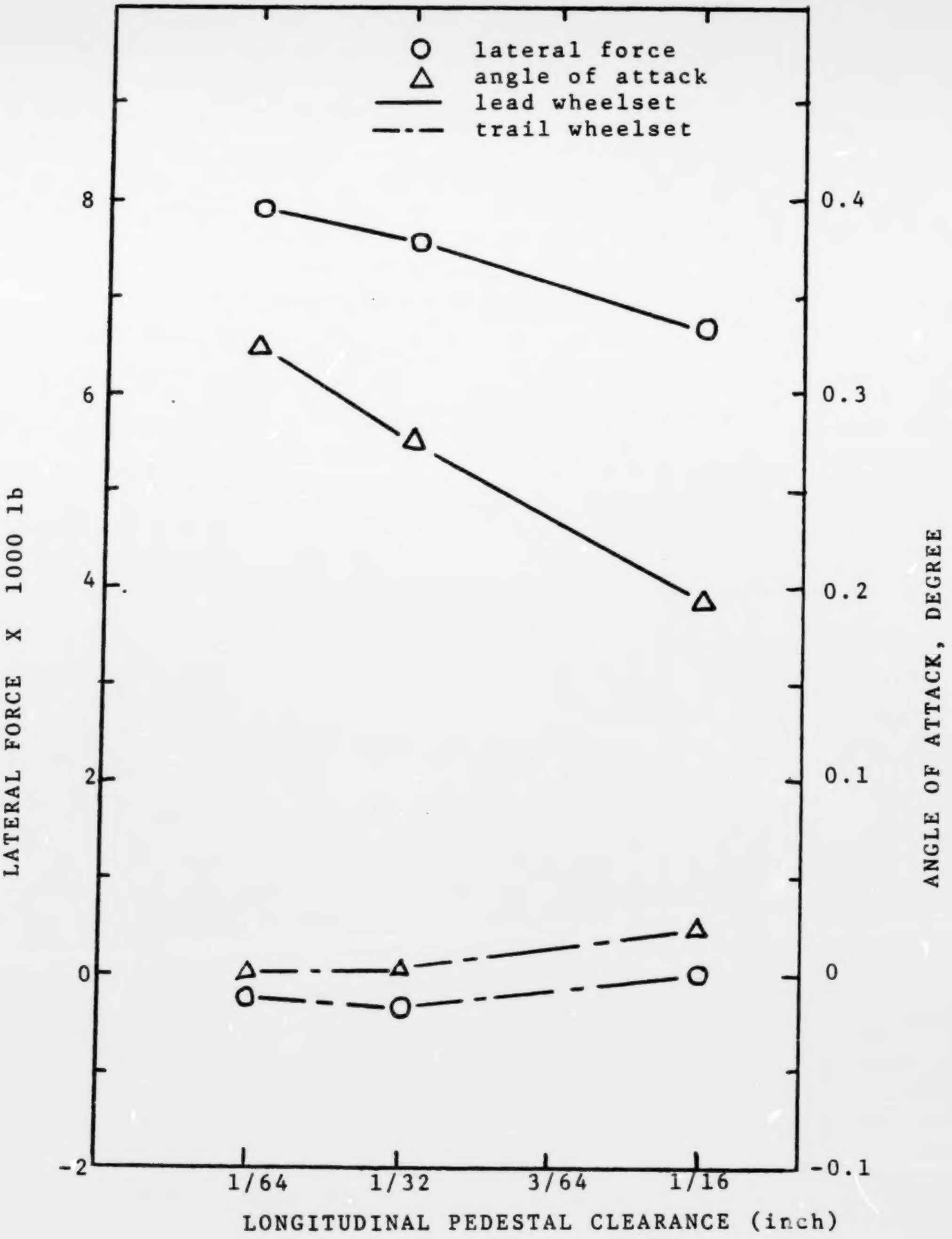


FIGURE 14 - EFFECT OF LONGITUDINAL CLEARANCE ON LATERAL FORCE AND ANGLE OF ATTACK: MAXIRIDE TRUCK, 6.2° CURVE, BALANCE SPEED

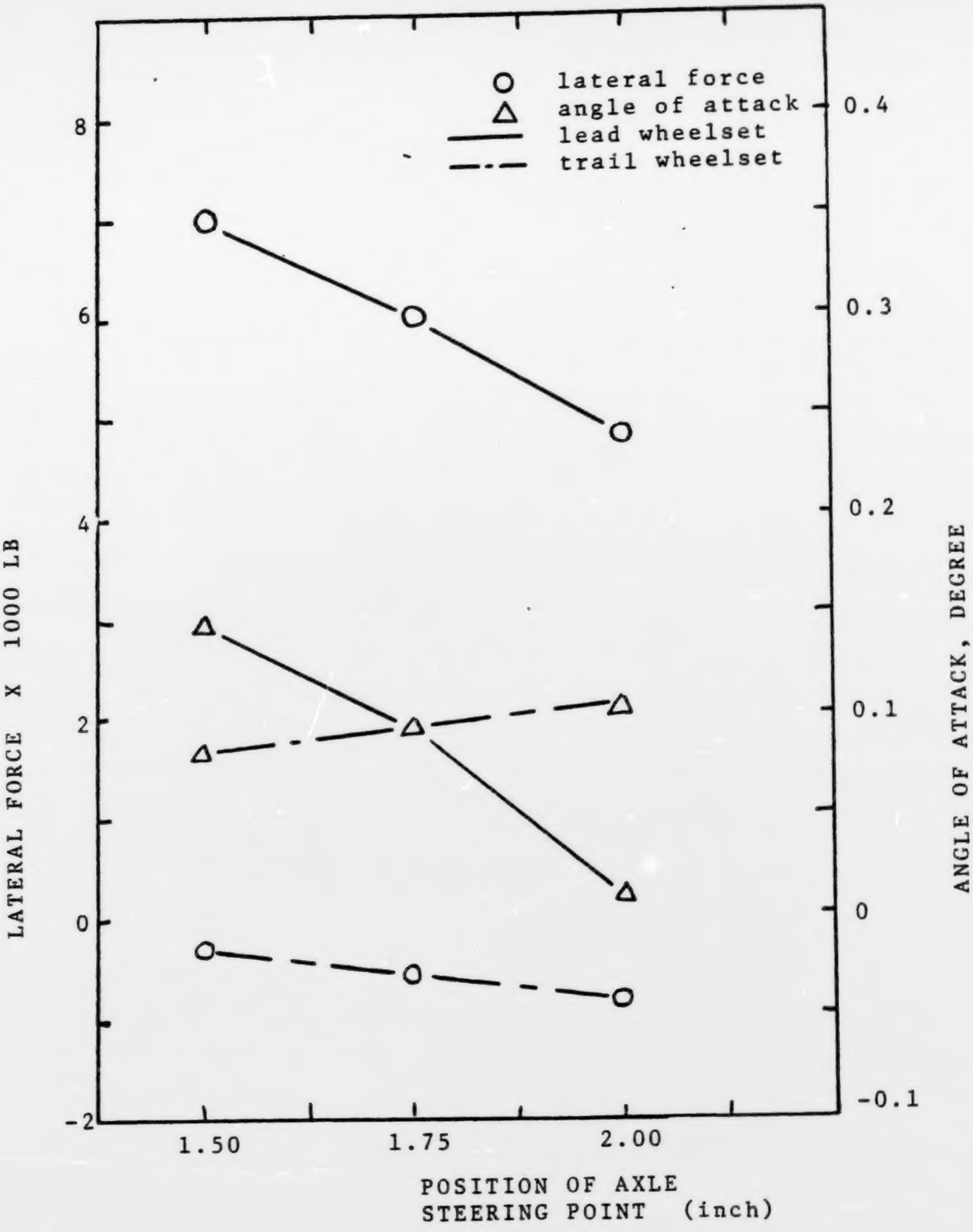


FIGURE 15 - EFFECT OF STEERING POINT POSITION ON LATERAL FORCE AND ANGLE OF ATTACK: DEVINE-SCALES TRUCK, 6.2° CURVE, BALANCE SPEED

TRUCK	LATERAL (PARALLELOGRAM) STIFFNESS:		LONGITUDINAL STIFFNESS:		DIRECT INTER-AXLE STIFFNESS:	
	(1000xlb/in)	LEVEL(1)	(1000xlb/in)	LEVEL(1)	(1000xlb/in)	LEVEL(1)
TYPE I	1.17	L	500	H	None	-
DR-1	0.50	L	15	M	36	M
BARBER-SCHEFFEL	0.50	L	7.5	M	9	M
SWING MOTION	500	H	500	H	None	-
ACF FABRICATED	500	H	30	M	None	-
MAXIRIDE	14	M	7(2)	L	None	-
DEVINE-SCALES(3)	200	H	1	L	None	-

TABLE 1 - COMPARISON OF ESTIMATED STIFFNESSES FOR TYPE I AND TYPE II TRUCKS

(1) The symbols L, M, H refer to low, medium and high values of stiffnesses respectively.

(2) Longitudinal stiffness is effective only over 1/32" (assumed longitudinal pedestal clearance), after which a very large stiffness is used.

(3) Stiffnesses for body link and axle steering link are assumed to be (50×10^3) and (200×10^3) lb/in respectively.

TYPE OF TRUCK SIMULATED	CURVATURE (deg)	SUPERELEVATION (in)	VEHICLE SPEED		
			10 MPH BELOW BALANCE	BALANCE SPEED (mph)	7 MPH ABOVE BALANCE
I, II	2.5	4.09	38.5	38.5	55.5
I	3.0	3.22	29.3	39.3	46.3
I, II	3.7	3.72	28.1	38.1	45.1
I	5.0	4.79	27.1	37.1	44.1
II	5.1	4.88	27.0	37.0	44.0
I	5.2	5.08	27.5	37.5	44.5
I, II	6.2	4.98	24.0	34.0	41.0

TABLE 2 - LIST OF SIMULATED TEST OPERATIONAL CONDITIONS

TRUCK	SENSITIVITY (lb/deg) Empty vehicle		SENSITIVITY (lb/deg) Loaded vehicle	
	MODEL	TEST	MODEL	TEST
TYPE I				
ASF RIDE CONTROL	-	-	1100	1600
TYPE II				
DR-11	600	300	1500	2000
BARBER-SCHEFFEL	400	800	1500	1600
DEVINE-SCALES	700	300	1400	1400
MAXIRIDE	400	500	1700	1800
SWING MOTION	500	400	1600	2300

TABLE 3 - COMPARISON OF SENSITIVITY OF LATERAL FORCE VERSUS CURVATURE - TYPE I AND TYPE II TRUCKS

TRUCK	SENSITIVITY (lb/mph) Empty vehicle		SENSITIVITY (lb/mph) Loaded vehicle	
	MODEL	TEST	MODEL	TEST
TYPE II				
DR-1	40	80	120	280
BARBER-SCHEFFEL	40	50	115	180
DEVINE-SCALES	35	65	115	210
MAXIRIDE	40	90	110	240
SWING MOTION	40	150	105	250

TABLE 4 - COMPARISON OF SENSITIVITY OF LATERAL FORCE VERSUS SPEED - TYPE II TRUCKS, 5.1° CURVE

TRUCK	PARAMETER	RANGE (x1000 lb/in)	EFFECT ON[1] LEADING WHEELSET	EFFECT ON[1] TRAILING WHEELSET
TYPE II:				
DR-1	inter-axle lateral stiffness	10 to 72	1	1
DR-1	longitudinal stiffness	7.5 to 30	3	1
BARBER-SCHEFFEL	inter-axle lateral stiffness	4.5 to 18	1	2
BARBER-SCHEFFEL	longitudinal stiffness	3.75 to 15	2	2
DEVINE-SCALES	lateral primary suspension stiffness	50 to 200	1	2
DEVINE-SCALES	body steering link stiffness	25 to 200	0	0

TABLE 5 - SUMMARY OF LATERAL FORCE SENSITIVITY TO TRUCK STIFFNESSES (page 1 of 2)

[1] The effects have been classified into four groups based on the change in the lateral force at the outer wheel
(0) = no change (1) = 0 to 750 lb (2) = 750 lb to 1500 lb
(3) = greater than 1500 lb

TRUCK	PARAMETER	RANGE (x1000 lb/in)	EFFECT ON[1.] LEADING WHEELSET	EFFECT ON[1.] TRAILING WHEELSET
TYPE II:				
ACF FABRICATED	parallelogramming stiffness	15 to 60	1	1
ACF FABRICATED	longitudinal stiffness	100 to 500	2	0
SWING MOTION	parallelogramming stiffness	100 to 500	1	0
TYPE I:				
ASF RIDE CONTROL	parallelogramming stiffness	0.5 to 5	1	3

TABLE 5 - SUMMARY OF LATERAL FORCE SENSITIVITY TO TRUCK STIFFNESSES (page 2 of 2)

TRUCK	PARAMETER	RANGE	EFFECT ON[1] LEADING WHEELSET	EFFECT ON[1] TRAILING WHEELSET
TYPE II:				
MAXIRIDE	longitudinal pedestal clearance	$\frac{1}{64}$" to $\frac{1}{16}$"	2	1
MAXIRIDE	lateral pedestal clearance	$\frac{1}{4}$" to $\frac{3}{4}$"	0	0
SWING MOTION	lateral axle-to-bearing clearance	0" to $\frac{1}{8}$"	1	1
DEVINE-SCALES	position of axle steering point	1.5" to 2"	3	1
TYPE I:				
ASF RIDE CONTROL	wheel dismatch mismatch	-3 to +3 tape sizes	3	3
ASF RIDE CONTROL	wheel profile	AAR 1/20 CN Heumann	1	3

TABLE 6 - SUMMARY OF LATERAL FORCE SENSITIVITY TO TRUCK CLEARANCES, WHEEL GEOMETRY, AND POSITION OF AXLE STEERING POINT

[1] see footnote Table 5

TRUCK	PARAMETER	RANGE	EFFECT ON[1] LEADING WHEELSET	EFFECT ON[1] TRAILING WHEELSET
TYPE II:				
DR-1	coefficient of friction	0.3 to 0.5	2	1
BARBER-SCHEFFEL	coefficient of friction	0.3 to 0.5	2	1
DEVINE-SCALES	coefficient of friction	0.3 to 0.5	1	1
MAXIRIDE	coefficient of friction	0.3 to 0.5	1	1
SWING MOTION	coefficient of friction	0.3 to 0.5	2	2
ACF FABRICATED	coefficient of friction	0.3 to 0.5	2	2
TYPE 1:				
ASF RIDE CONTROL	coefficient of friction	0.15 to 0.45	3	3

TABLE 7 - SUMMARY OF LATERAL FORCE SENSITIVITY TO COEFFICIENT OF FRICTION BETWEEN WHEEL AND RAIL

[1] see footnote Table 5

REFERENCES

1. Porter, S.R.M.; The Mechanics of a Locomotive on Curved Track. The Railway Gazette, London, 1935.

2. Smith, K.R.; MacMillan, R.D.; Martin, G.C.; 2, 3 and 4 Axle Rigid Truck Curve Negotiation Model - Technical Documentation. Track-Train Dynamics report R-206, AAR, Chicago, Ill.

3. Newland, D.E.; Steering a Flexible Railway Truck on Curved Track.Transactions of the ASME. Journal of Engineering for Industry, August 1969.

4. Boocock, D.; The Steady-State Motion of Railway Vehicles on Curved Track. Journal of Mechanical Engineering Science vol. no 6, 1969.

5. Vermeulen, P.J.; Johnson, K.L.; Contact of Non-spherical Elastic Bodies Transmitting Tangential Forces. Journal of Applied Mechanics, June 1964.

6. Borgeaud, G.; Le Passage en Courbes de Véhicules de Chemin de Fer, dont les Essieux Fournissent un Effort de Traction Continu. Thèse présentée à l'Ecole Polytechnique fédérale, Zurich 1937.

7. Ghonem, H.; Kalousek, J.; The Use of Angle-of-Attack Measurements to Estimate Rail Wear under Steady State Rolling Conditions. Presented at the International Conference on Wheel/Rail Load and Displacement Measurement Techniques, Boston, January 19, 20, 1981.

8. Truck Design Optimization Project Phase II; Performance Specification for Type II Trucks, FRA/ORD-81-361, August 1981. Wyle Laboratories, Colorado Springs, Co.

9. Marcotte, P.P.; Mathewson, K.J.R.; Caldwell, W.N.; Improved Wheel Tread Profiles for Heavy Freight Vehicles. ASME Journal of Engineering for Industry, August 1980, vol. 102.

APPENDIX I

TECHNICAL ASPECTS AND EQUATIONS OF MOTION OF THE MODEL

This section describes specific technical details of the model, the equations of motion, and provides sample lists of the input parameters and output results.

NOMENCLATURE

(ab)	product of semi-axes lengths of contact ellipse
b_t, b_f	half kinematic gauges for the tread and flange
c	Kalker creep coefficient
e_x, e_y, e_z	longitudinal, lateral and vertical distances between points of tread and flange contact
G	shear modulus of elasticity
r_o, r_{act}	nominal radius of wheel tread and actual radius due to lateral displacement of wheelset
r_{f1}, r_{f2}	actual radii from centreline of axle to points of flange contact for outer and inner wheels
w	half truck wheelbase
R_c	radius of curvature of the track
F_y	net external lateral force from vehicle body due to centrifugal acceleration and lateral coupler forces
M_{roll}	net roll moment from vehicle body due to centrifugal acceleration and lateral coupler forces
W_1, W_2	vertical loads applied to truck at axle bearings of outer and inner wheels
T_{act}	actual torque applied to wheelset
q_i	lateral, longitudinal, yaw and rotational degrees of freedom of leading and trailing wheelset ($i = 1, 8$)
q_i	lateral, yaw degrees of freedom of truck frame ($i = 9, 10$)
q_t	lateral tracking error of wheelset
θ	angle of attack between wheelset and rail
γ	angle between vertical axis and radial line to point of flange contact

μ_c, μ_f	coefficients of friction at tread and flange respectively
ξ, ξ_u, ξ_v	total creepage, lateral, and longitudinal components in the plane of wheel/rail contact

VARIABLES HAVING A SPECIFIC SUBSCRIPT NOTATION

F_c, F_{cij}	tread creep force
F_f, F_{fij}	flange normal force
F_t, F_{tij}	flange tangential (friction) force
F_n, F_{nj}	tread normal force
F_{ei}	elastic force or moment between wheelset and truck frame

where: $i = x, y, z, \Theta$ denoting components in the longitudinal, lateral, vertical and yaw directions of local wheelset coordinates respectively (' primed components are in truck coordinate system).

: $j = 1, 2$ denoting outer and inner wheels.

WHEELSET CREEPAGES

Exact expressions for the lateral and longitudinal creepages ξ_u and ξ_v respectively, have been derived for the points of contact of both the tread and flange. The equations which are not shown have the form:

$$\xi_u = f_u\ (\alpha,\ q_i,\ r_{act},\ r_o,\ b_t, R_c,\ b_f) \quad \ldots \quad (1)$$

$$\xi_v = f_v\ (\alpha,\ q_i,\ r_{act},\ r_o,\ b_t, R_c,\ b_f) \quad \ldots \quad (2)$$

where: f_u and f_v are geometric functions.

: $\alpha = \Theta$ .... for tread contact.

: $\alpha = f(\Theta, \beta)$..... for flange contact.

: q_1 = dimensionless rotational velocity.

The total creepage ξ is found by taking the vector sum of ξ_u and ξ_v. Spin creepage effects on the wheelset are neglected in the model.

CREEP FORCES

The creep force at the wheel tread is determined from Vermeulen and Johnson's nonlinear formulation of creep force versus creepage [5] , and is given by equation (3).

$$F_c = \mu_c F_n \left\{ 1 + \left[\frac{G\pi ab}{\Phi} \frac{\xi}{3\mu_c F_n} - 1 \right]^3 \right\} \quad \ldots \quad (3)$$

Although the formulation was tested experimentally for longitudinal and lateral creepages separately, it is assumed to be valid for the combined total creepage as well. The term $(G\pi ab/\Phi)$ in equation (3) is identical to Kalker's linear creep coefficient "f", and (π/Φ) identical to the Kalker coefficient "c". The values of "ab", the product of the semi-axes of the contact ellipse and "c" are calculated from curve-fit equations based on Hertz contact theory and tables of Kalker coefficients. It should be noted that the value of "c" used in the model is the mean value of Kalker coeffients in the lateral and longitudinal directions.

The force between the flange and rail consists of normal and tangential components. The normal force F_f is modelled by a stiff linear spring between the flange and the rail in the lateral direction. The tangential force F_t is assumed to be saturated at the point of flange contact and has a magnitude given by equation (4):

$$F_t = \mu_f F_f \qquad \ldots. \quad (4)$$

The direction of F_t is calculated from the exact creepages at the point of contact.

The components of the creep forces F_c and F_t in the lateral, longitudinal and vertical directions are then calculated based on the ratio of the component creepages to the total creepage.

EQUATIONS OF MOTION

Each wheelset of the truck has four equations of motion, one for each degree of freedom, and two equations for force balance in the vertical/roll plane. The six equations for each wheelset are:

$$\left(F_{cy1} + F_{ty1} + F_{fy1}\right) + \left(F_{cy2} + F_{ty2} + F_{fy2}\right) + F_{ey} = 0 \quad \ldots (5)$$

$$\left(F_{cx1} + F_{tx1}\right) + \left(F_{cx2} + F_{tx2}\right) + F_{ex} = 0 \quad \ldots. (6)$$

$$b_t\left(F_{cx1} - F_{cx2}\right) + \Theta b_t\left(F_{cy1} - F_{cy2}\right) + \left(b_f\right)\left(F_{tx1} - F_{tx2}\right) + \left(e_x - \Theta b_f\right)\left[\left(F_{fy1} - F_{fy2}\right) + \left(F_{ty1} - F_{ty2}\right)\right] + F_{ea} = 0 \quad \ldots. (7)$$

$$r_{t1}F_{cx1} + r_{t2}F_{cx2} + \left(r_{f1}\cos\gamma\right)\left(F_{tx1}\right) + \left(r_{f2}\cos\gamma\right)\left(F_{tx2}\right) + \left(r_{f1}\sin\gamma\right)\left(F_{tz1} + F_{fz1}\right) + \left(r_{f2}\sin\gamma\right)\left(F_{tz2} + F_{fz2}\right) + T_{act} = 0 \quad \ldots. (8)$$

$$\left(F_{n1} + F_{n2}\right) + \left(F_{fz1} + F_{fz2} + F_{tz1} + F_{tz2}\right) = W_1 + W_2 \quad \ldots. (9)$$

$$\left(b_t + q_t\right)\left(F_{n2}\right) - \left(b_t - q_t\right)\left(F_{n1}\right) + \left(b_f + q_t\right)\left(F_{fz2} + F_{tz2}\right) + \left(b_f - q_t\right)\left(F_{fz1} + F_{tz1}\right) + F_{ey}r_o + M_{roll} + b_t\left(W_1 - W_2\right) = 0 \quad \ldots. (10)$$

The equations of motion on the truck frame are:

$$\sum_{k=1}^{2}\left(F'_{ey}\right)_k + F_y = 0 \quad (11)$$

$$\sum_{k=1}^{2}\left(F'_{ea}\right)_k + w\left(F'_{ey1} - F'_{ey2}\right)_k = 0 \quad (12)$$

Note that the terms for the elastic forces in equations (11) and (12) are primed, as they are the resultant elastic forces in the local coordinate system of the truck. k=1, 2 denotes the forces on the leading and trailing wheelsets respectively.

The following is a sample list of parameters for a Type I truck with standard AAR wheel profiles - loaded car - on the 2.5° curve and at the balance speed.

```
          RUN W-1-101,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
              26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
              DEG  2.50    SPEED  48.5    SUPERELEVATION  4.09

         TRUCK CURVING PROGRAM. (23/03/81).
      <<<  2 - AXLE NON-RIGID-FRAME TRUCK  >>>
     INPUT PARAMETERS:
  #                DESCRIPTION:                                VALUE:

     VEHICLE:
   1        HALF WHEELBASE.                                 243.00000
   2        EQUIV. HEIGHT OF C/G ABOVE RAILHEAD.             86.04000
   3        HEIGHT OF COUPLER ABOVE RAILHEAD.                33.00000
     TRUCK:
   4        HALF WHEELBASE.                                  35.00000
   5        TRUCK CENTRE TO BEARINGS (LATERAL).              39.50000
   6        RAILHEAD TO TRACTION PAD.                         0.00000
   7        RAILHEAD TO AXLE INTERCONNECTION.                 0.00000
     TRACK:
   8        HALF KINEMATIC GAUGE.                            29.75000
   9        RAILHEAD RADIUS.                                 10.00000
  10        SUPERELEVATION DEFICIENCY.                       -0.00643
  11        RAIL TOP TO FLANGE CONTACT LEVEL.                 0.32000
     MISC.:
  12        FRICTION COEFF. AT TREAD CONTACT.                 0.30000
  13        FRICTION COEFF. AT FLANGE CONTACT.                0.30000
  14        FLANGE CLEARANCE.                                 0.50000
  15        FLANGE- TO TREAD-CONTACT (LATERAL).               1.38000
  16        DIMENSIONLESS TRACTIVE EFFORT.                    0.00000
  17        CREEP COEFFICIENT FACTOR.                         0.70000
  18        EXTERNAL LATERAL FORCE PER TRUCK.                 0.00000
     WHEELS:                         (+ = OUT; - = IN).
  19        INITIAL LOAD: HIGH RAIL:  LEAD(L).            29663.00000
  20                                 TRAIL(T).            29663.00000
  21                                CENTRE(C).                0.00000
  22                     LOW RAIL:        (L).            29663.00000
  23                                      (T).            29663.00000
  24                                      (C).                0.00000
  25        MEAN RADIUS AT CENTRAL AXLE   (L).               18.00000
  26                         POSITIONS:   (T).               18.00000
  27                                      (C).                0.00000
  28        DIFFERENCE IN RADII:          (L).                0.00000
  29         (HIGH RAIL - LOW RAIL).      (T).                0.00000
  30                                      (C).                0.00000
  31        FLANGE CONTACT PLANE ANGLE. (DEG).               62.50000
  32        TREAD CONICITY.                                   0.05000
     STIFFNESSES:
  33        FLANGE CONTACT (LATERAL).                   1000000.00000
  34        TRUCK YAW (+ = LEAD; - = TRAIL).                  0.00000
  35        TRUCK/AXLE (LATERAL).         (L).             1170.00000 (1)
  36          FOR GIBBS DISPLACEMENT.     (T).             1170.00000
  37          (PER AXLE).                 (C).                0.00000
  38        TRUCK/AXLE (LONGITUDINAL)     (L).           500000.00000 (2)
  39        (PER WHEEL) HIGH RAIL SIDE:   (T).           500000.00000
  40                                      (C).                0.00000
  41                    LOW RAIL SIDE:    (L).           500000.00000
  42                                      (T).           500000.00000
  43                                      (C).                0.00000
```

```
44        INTER-AXLE (LATERAL).                                0.00000
   AXLE CLEARANCES:
45        HALF FREE PLAY, AXLE/BEARING. (L).                   0.00000
46                                      (T).                   0.00000
47                                      (C).                   0.00000
48        HALF TOTAL GIBBS CLEARANCE ON (L).                   0.92000(1)
49                       ONE SIDE ONLY. (T).                   0.92000
50                                      (C).                   0.00000
51        HALF TOTAL PEDESTAL CLEARANCE.(L).                 100.00000(2)
52                          (HIGH RAIL)(T).                  100.00000
53                                      (C).                   0.00000
54                           (LOW RAIL)(L).                  100.00000
55                                      (T).                 100.00000
56                                      (C).                   0.00000
   TRAM ERRORS:
57        LATERAL AXLE ERROR.           (L).                   0.00000
58                                      (T).                   0.00000
59                                      (C).                   0.00000
60        LONGITUDINAL AXLE ERROR.      (L).                   0.00000
61                                      (T).                   0.00000
62                                      (C).                   0.00000
63        YAW AXLE ERROR.               (L).                   0.00000
64                                      (T).                   0.00000
65                                      (C).                   0.00000
66        LATERAL TRUCK ERROR.                                 0.00000
67        YAW TRUCK ERROR.                                     0.00000
```

(1) The truck frame is assumed to have a low value of parallelogramming stiffness up to amplitudes of 1.85", where it becomes more rigid.

(2) The truck frame is assumed to prevent any steering motion of the wheelsets relative to one another.

The following are samples of the short and full output lists for simulation runs of the Type I truck given in the sample input list.

Symbols used in the sample short output lists are defined as:

L	lateral wheel/rail force on the outer wheel
L/V	ratio of the lateral-to-vertical wheel/rail forces on the outer wheel
ANGLE	angle of attack of the wheelset with respect to the radial line of the curve

Symbols used in the sample full output list are defined below.

QT	wheelset lateral tracking error
TH	wheelset angle of attack
QAR	wheelset dimensionless rotational velocity
QAX	wheelset longitudinal displacement
QTY	truck frame lateral displacement
QTA	truck frame yaw displacement
GAM	γ (see Nomenclature p. I-1).
FEAY	lateral elastic force between wheelset and frame
FEAX	longitudinal elastic force between wheelset and frame
FEAA	yaw moment between wheelset and frame
FETY	total lateral elastic force on truck frame
FETA	total yaw moment on truck frame
FINT	inter-axle lateral force
L/V	ratio of the lateral-to-vertical force on a wheel
L	net lateral wheel/rail force
V	net vertical wheel/rail force
FF, FFY, FFZ	total flange normal force of a wheel and its components in the Y and Z coordinates respectively
FT, FTX, FTY, FTZ	total flange tangential force of a wheel and its components in the X, Y and Z coordinates respectively
RF	radius of the wheel at the point of flange contact

ZFT, ZFU, ZFV	total flange creepage with respect to the rail and its components in the longitudinal and transverse directions at the point of contact respectively
FN	normal wheel/rail force at the wheel tread
FC, FCX, FCY	total tread creep force of a wheel and its components in the X and Y coordinates recpectively
RT	radius of the wheel at the point of tread contact
SF	creep coefficient
ZTT, ZTX, ZTY	total tread creepage with respect to the rail and its components in the X and Y coordinates respectively
CRP	percentage of creep saturation of the wheel tread
EROL	rolling resistance of the wheel as calculated from energy considerations
FROL	rolling resistance of the wheelset as calculated from force considerations

```
RUN W-1-101,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  2.50     SPEED  48.5    SUPERELEVATION  4.09
LEAD:          L    4362.   L/V 0.14       ANGLE-0.135
TRAIL:         L      91.   L/V 0.00       ANGLE 0.002

RUN W-1-102,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  3.00     SPEED  39.3    SUPERELEVATION  3.22
LEAD:          L    5179.   L/V 0.17       ANGLE-0.166
TRAIL:         L      60.   L/V 0.00       ANGLE 0.001

RUN W-1-103,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  3.70     SPEED  38.1    SUPERELEVATION  3.72
LEAD:          L    6158.   L/V 0.20       ANGLE-0.208
TRAIL:         L      22.   L/V 0.00       ANGLE 0.001

RUN W-1-104,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  5.00     SPEED  37.1    SUPERELEVATION  4.79
LEAD:          L    7705.   L/V 0.25       ANGLE-0.309
TRAIL:         L     847.   L/V 0.03       ANGLE-0.024

RUN W-1-105,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  5.20     SPEED  37.5    SUPERELEVATION  5.08
LEAD:          L    7947.   L/V 0.26       ANGLE-0.334
TRAIL:         L    1338.   L/V 0.04       ANGLE-0.036

RUN W-1-106,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  6.20     SPEED  34.0    SUPERELEVATION  4.98
LEAD:          L    8650.   L/V 0.28       ANGLE-0.458
TRAIL:         L    3514.   L/V 0.12       ANGLE-0.102

RUN W-1-111,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  2.50     SPEED  55.5    SUPERELEVATION  4.09
LEAD:          L    5018.   L/V 0.16       ANGLE-0.119
TRAIL:         L     757.   L/V 0.02       ANGLE 0.018

RUN W-1-112,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  3.00     SPEED  46.3    SUPERELEVATION  3.22
LEAD:          L    5846.   L/V 0.18       ANGLE-0.150
TRAIL:         L     718.   L/V 0.02       ANGLE 0.017

RUN W-1-113,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  3.70     SPEED  45.1    SUPERELEVATION  3.72
LEAD:          L    6986.   L/V 0.22       ANGLE-0.190
TRAIL:         L     816.   L/V 0.03       ANGLE 0.019

RUN W-1-114,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
    26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
    DEG  5.00     SPEED  44.1    SUPERELEVATION  4.79
LEAD:          L    8845.   L/V 0.27       ANGLE-0.282
TRAIL:         L    1758.   L/V 0.05       ANGLE 0.003
```

```
             RUN W-1-101,    TYPE I TRUCK: 100 TON,1/20 (PARALLEL'G)
                 26/03/81; PF.010 (24/03/81) NO MODS; DSL-3 (23/03/81)
                 DEG  2.50    SPEED  48.5    SUPERELEVATION  4.09
     QT:            0.510031            0.107795
     TH:           -0.002358            0.000038
    QAR:            0.999216            1.000003
    QAX:           -0.000082            0.000001
    QTY,QTA:        0.308913           -0.001164

    GAM:(<=.275)   -0.004529            0.000074

   FEAY:               -188.                188.
   FEAX:                 82.                 -1.
   FEAA:            -122835.             109699.
   FETY,FETA:             0.                  0.
   FINT:                  0.


                      LEAD:              TRAIL:              CENTRE:
                OUTER     INNER     OUTER     INNER     OUTER     INNER

    L/V:      0.144271  0.156586  0.003050 -0.003060
      L:         4362.     4556.       91.      -90.
      V:        30233.    29093.    29820.    29506.


     FF:        10031.        0.        0.        0.
    FFY:        -8898.        0.        0.        0.
    FFZ:         4632.        0.        0.        0.

     FT:         3009.        0.        0.        0.
    FTX:         2882.        0.        0.        0.
    FTY:          399.        0.        0.        0.
    FTZ:          767.        0.        0.        0.
     RF:       18.3452   18.3452   18.3450   18.3450

    ZFU:     -0.017167  0.000000  0.000000  0.000000
    ZFV:     -0.005150  0.000000  0.000000  0.000000
    ZFT:      0.017923  0.000000  0.000000  0.000000


     FN:        24834.    29093.    29820.    29506.

     FC:         4212.     5046.     1846.     1846.
    FCX:         -794.    -2171.    -1843.     1844.
    FCY:         4137.     4556.      -91.      -90.
     RT:       18.0255   17.9745   18.0054   17.9946

     SF:      2258594.  2508292.  2550925.  2532634.
    ZTX:      0.000453  0.001123  0.000779 -0.000785
    ZTY:     -0.002357 -0.002356  0.000038  0.000038
    ZTT:      0.002400  0.002610  0.000780  0.000786
    CRP:      0.242538  0.250030  0.074126  0.074994

EROL:            64.      13.        1.        1.
FROL:                 78.                  4.
```

APPENDIX II

TYPE I TRUCK STEADY-STATE CURVING SIMULATIONS

1.0 INTRODUCTION

This report presents a summary of the curving performance analyses of type I freight car trucks as determined from simulation runs using a mathematical truck curving model. The report consists of four sections, which are as follows:

1. Approach to Curving Performance Analysis
2. Results of Theoretical Curving Performance
3. Comparison of Theoretical and Experimental Results
4. Results of Parameter Sensitivity Analysis

2.0 APPROACH TO CURVING PERFORMANCE ANALYSIS

2.1 INTRODUCTION

The approach taken for the theoretical curving peformance analysis was to simulate the experimental curving tests of a type I(1) freight car truck which were conducted by Wyle Laboratories for TDOP Phase II. Values for the input parameters of the theoretical model were selected to represent the vehicle, truck and track as were known or estimated to exist during the tests. Outputs from the simulation correspond to performance parameters which were defined for the experimental tests. Comparison of theoretical and experimental results was then made. An additional aspect to the theoretical analysis was to determine the sensitivity of the truck's performance to a selected number of parameters (which were not studied during the tests).

2.2 OVERVIEW OF EXPERIMENTAL TESTS

The curving tests performed by Wyle Laboratories consisted of running a 100 ton hopper car with type I trucks over a test section of curved track. The section contains 9 curves having curvatures varying between 2.5 to 6.2 degrees. Three runs were conducted over the test section which provided data corresponding to conditions below, near, and above the balance speed of each curve. Data from the instrumentation was analyzed for each curve to give the mean values of the following items:

- lateral wheel/rail force
- wheel L/V ratio
- angle of attack

---

(1) Type I designates a conventional North-American three-piece frame freight car truck.

The first two items were determined for the outer wheel (on the high rail) of the lead wheelset of the lead truck. The last item was determined for the lead wheelset of the lead truck.

2.3 SELECTION OF MODEL INPUT PARAMETERS

A baseline vehicle was defined to represent a loaded 100 ton hopper car having two type I freight car trucks with standard AAR 1/20 tapered wheels in new condition. Values for the input parameters defining the vehicle were selected using data supplied by Wyle Laboratories (for example, vehicle weight, truck wheelbase). For data which was unknown (e.g. geometry of the rail, truck stiffness), engineering estimates were made for the parameter values, based on various assumptions which are stated in the report.

A second parameter set was selected to represent the same 100 ton hopper car in the empty condition. Values for this parameter set were identical to the baseline vehicle with the following exceptions:

- height of centre of gravity of car body set to 52.86 inches,
- initial vertical wheel/rail loads set to 8413 lb/wheel.

2.4 SELECTION OF OPERATING CONDITIONS

The operating conditions for the steady-state curving model are given by the degree of curvature and superelevation of the curve, and the speed at which the vehicle is traversing the curve. For the analysis of the curving performance of the type I truck, six curves and three speeds were selected.

The six curves correspond to six of the nine test curves[1] for which data was analyzed for TDOP and have curvatures ranging from 2.5 to 6.2 degrees, and superelevations from 3.22 to 5.08 inches. The three ranges of speeds were selected to represent the operation of the vehicle at the balance speed, 7 mph above, and 10 mph below the balance speed of each curve. These speeds correspond to the intended vehicle test speeds for the TDOP tests. A list of the six curves and their ranges of speeds is given in Table 2.1.

---

[1] Two of the nine test curves (5.1 and 6.1 degrees) were not simulated as their values of curvatures were close to those which were simulated. Also, since the model does not distinguish between left and right hand curves (except when there are input parameters which have different left/right values, such as "difference in (wheel) radii : high rail - low rail"), only the left-hand 6.2 degree curve was simulated. There was a tenth curve in the test section having a curvature of 1.2 degree. However, no experimental data was available for this curve, and so this curve was not simulated.

CURVATURE (deg)	SUPERELEVATION (in)	10 MPH BELOW BALANCE (mph)	BALANCE SPEED (mph)	7 MPH ABOVE BALANCE (mph)
2.5	4.09	38.5	48.5	55.5
3.0	3.22	29.3	39.3	46.3
3.7	3.72	28.1	38.1	45.1
5.0	4.79	27.1	37.1	44.1
5.2	5.08	27.5	37.5	44.5
6.2	4.98	24.0	34.0	41.0

TABLE 2.1 LIST OF OPERATING CONDITIONS

3.0 RESULTS OF THEORETICAL CURVING PERFORMANCE

This section describes the results of the theoretical curving analysis of the type I truck for the loaded (baseline) and empty vehicle configurations and the set of operating conditions in Table 2.1.

The results are given in terms of the following three measures of (curving) performance for the leading wheelset of the truck:

1) L : lateral wheel/rail force (of the outer wheel: that is, the wheel on the high rail of a curve).

2) L/V : the ratio of the lateral-to-vertical force on the outer wheel.

3) θ : the angle of attack of the wheelset with respect to the radial line of the curve.

Figures 3.1 to 3.6 are graphs of the three measures of curving performance for the leading wheelset (of the lead truck) of the loaded and empty cars. It can be seen that the same trends occurred for both vehicles: namely that,

1) Lateral force L and L/V ratio increase with increases in curvature for the same speed condition.

2) L and L/V also increase with speed for a given track curvature.

3) Angle of attack θ increases with curvature but decreases with speed.

The maximum values of the three measures of performance for each vehicle were found to occur at the condition of highest degree of curvature (that is, on the 6.2° curve), and were:

	loaded	empty
lateral force (lb)	10000	3100
L/V ratio	0.30	0.34
angle of attack (deg)	0.50	0.48

A comparison of the figures for the empty car and the loaded vehicle showed that:

- lateral wheel/rail forces on the leading outer wheel were higher for the loaded vehicle for the same operating conditions.

- the L/V ratios on that wheel were lower for the loaded vehicle for the same operating conditions.

- the angles of attack of the lead wheelset were approximately the same for empty or loaded conditions.

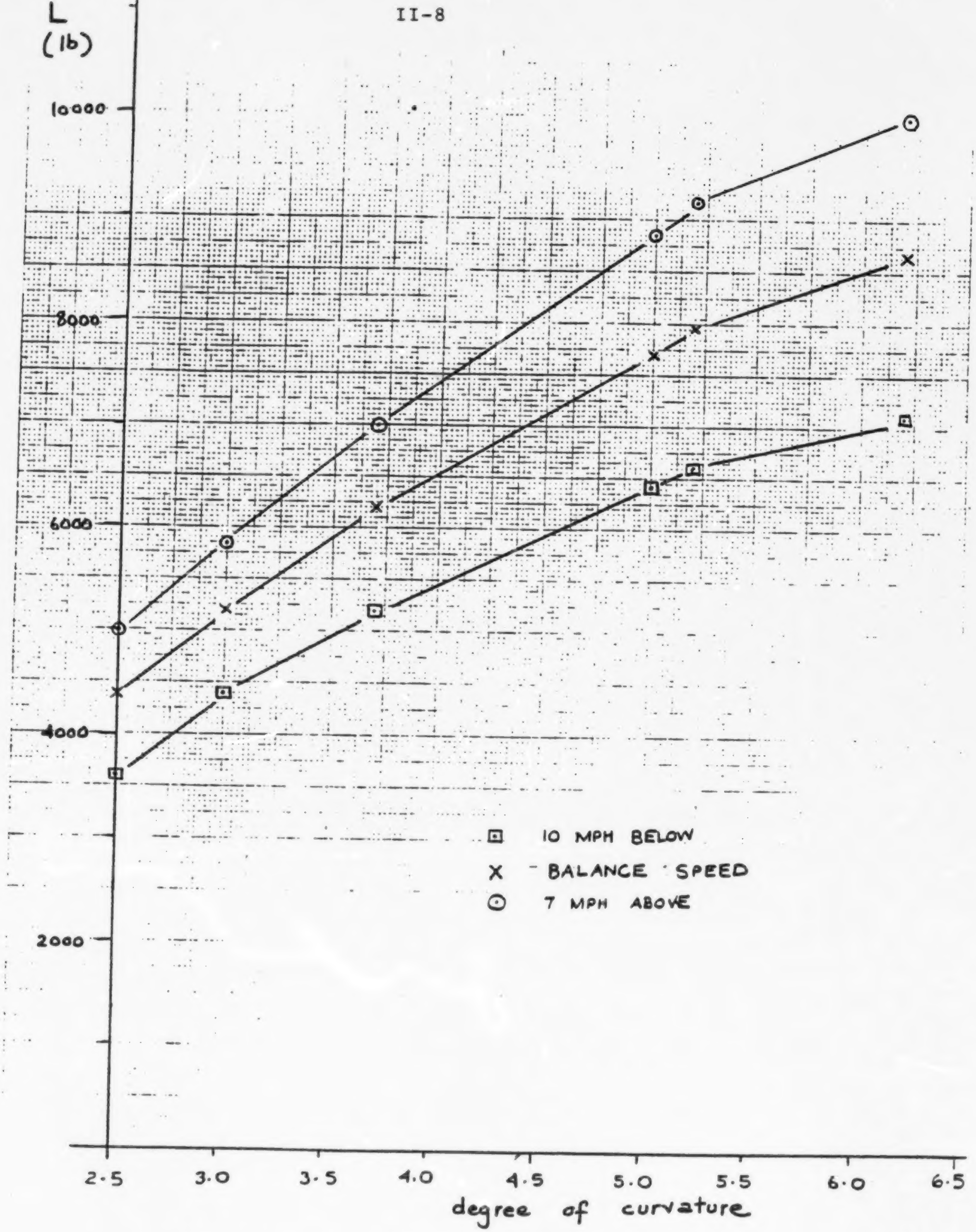


FIG. 3.1 LATERAL FORCE (OUTER LEAD WHEEL) - LOADED VEHICLE

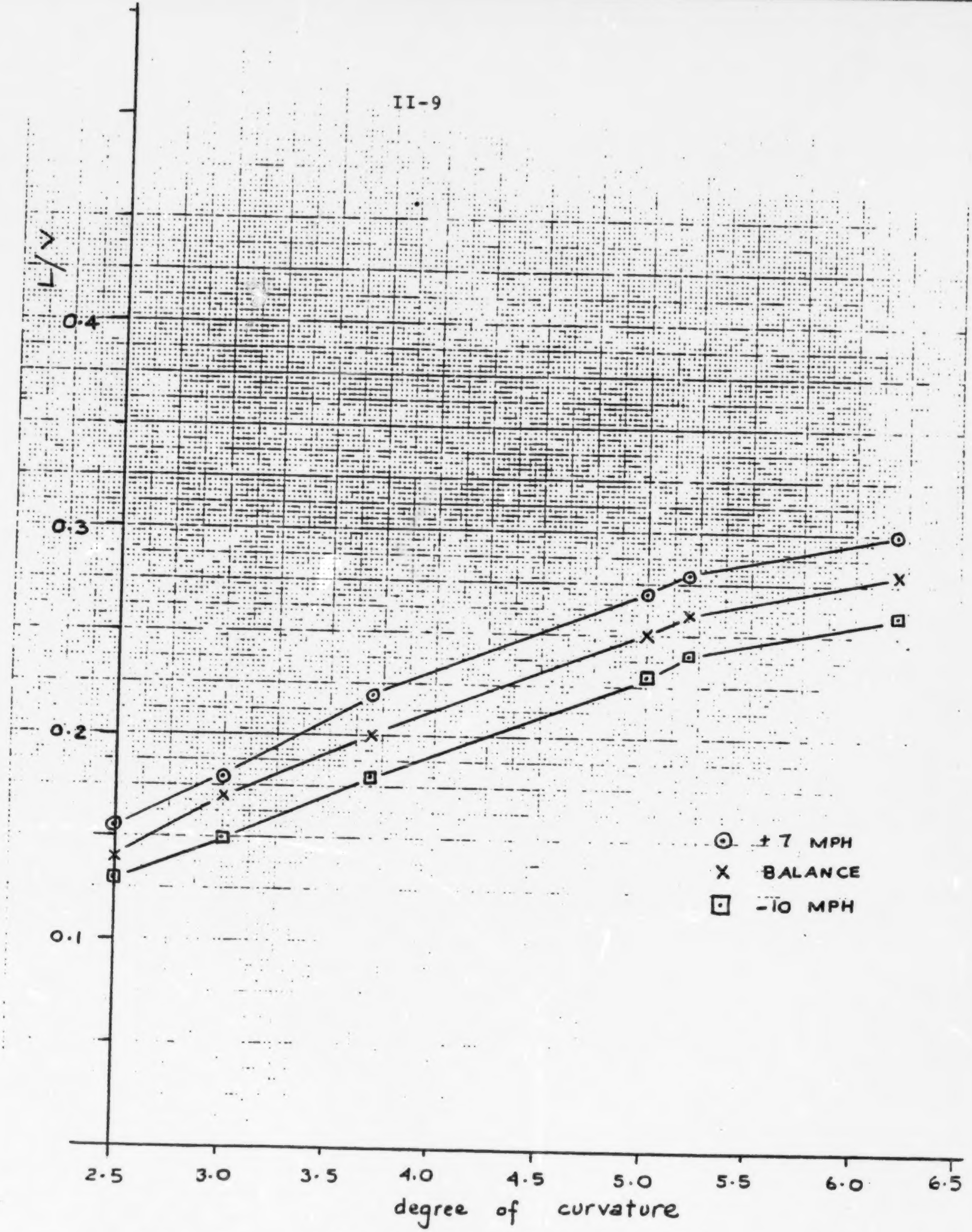


Fig 3.2 L/V RATIO (OUTER LEAD WHEEL)
: LOADED VEHICLE

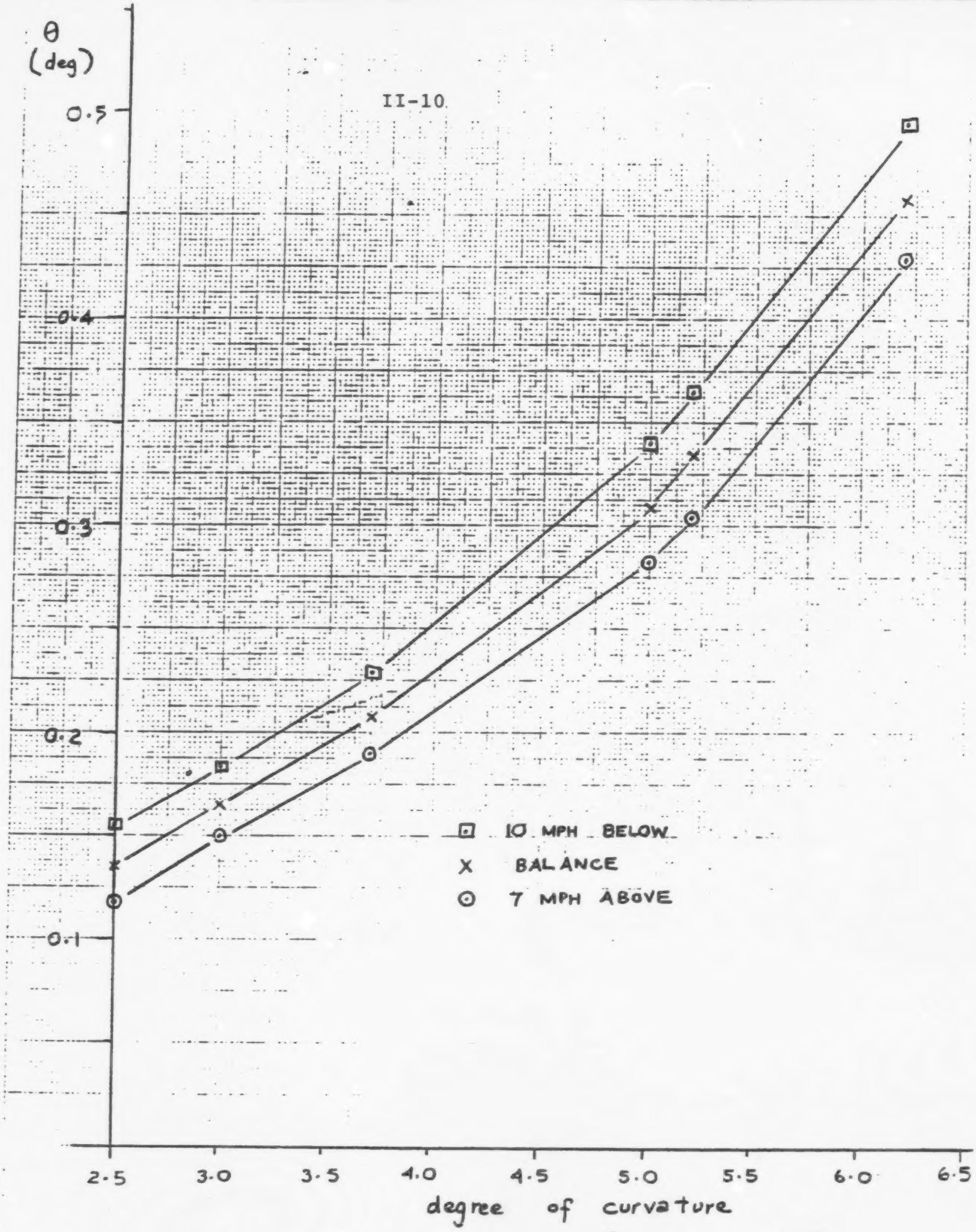


FIG. 3.3 ANGLE OF ATTACK (LEAD AXLE)
: LOADED VEHICLE

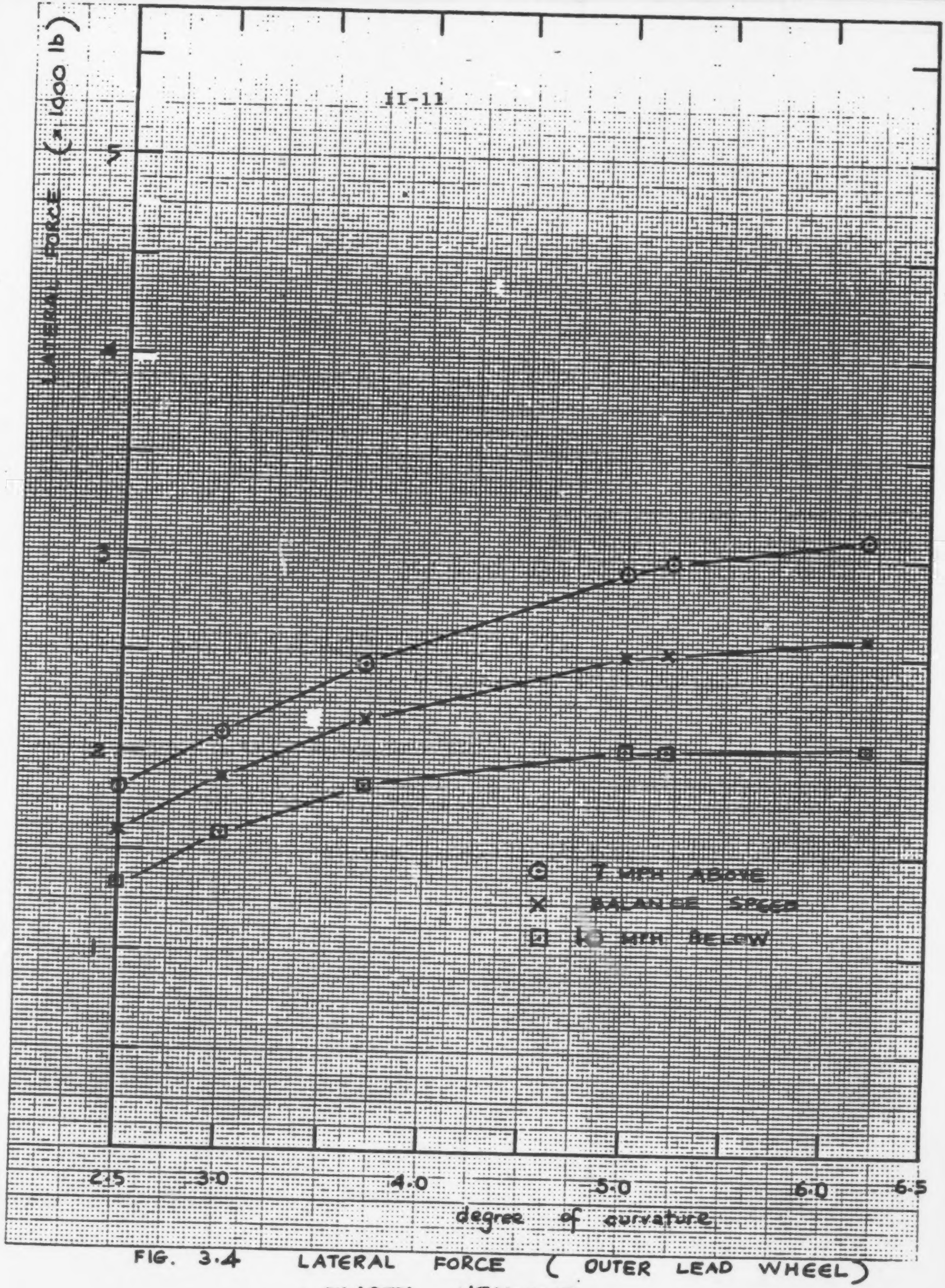


FIG. 3.4 LATERAL FORCE (OUTER LEAD WHEEL) : EMPTY VEHICLE

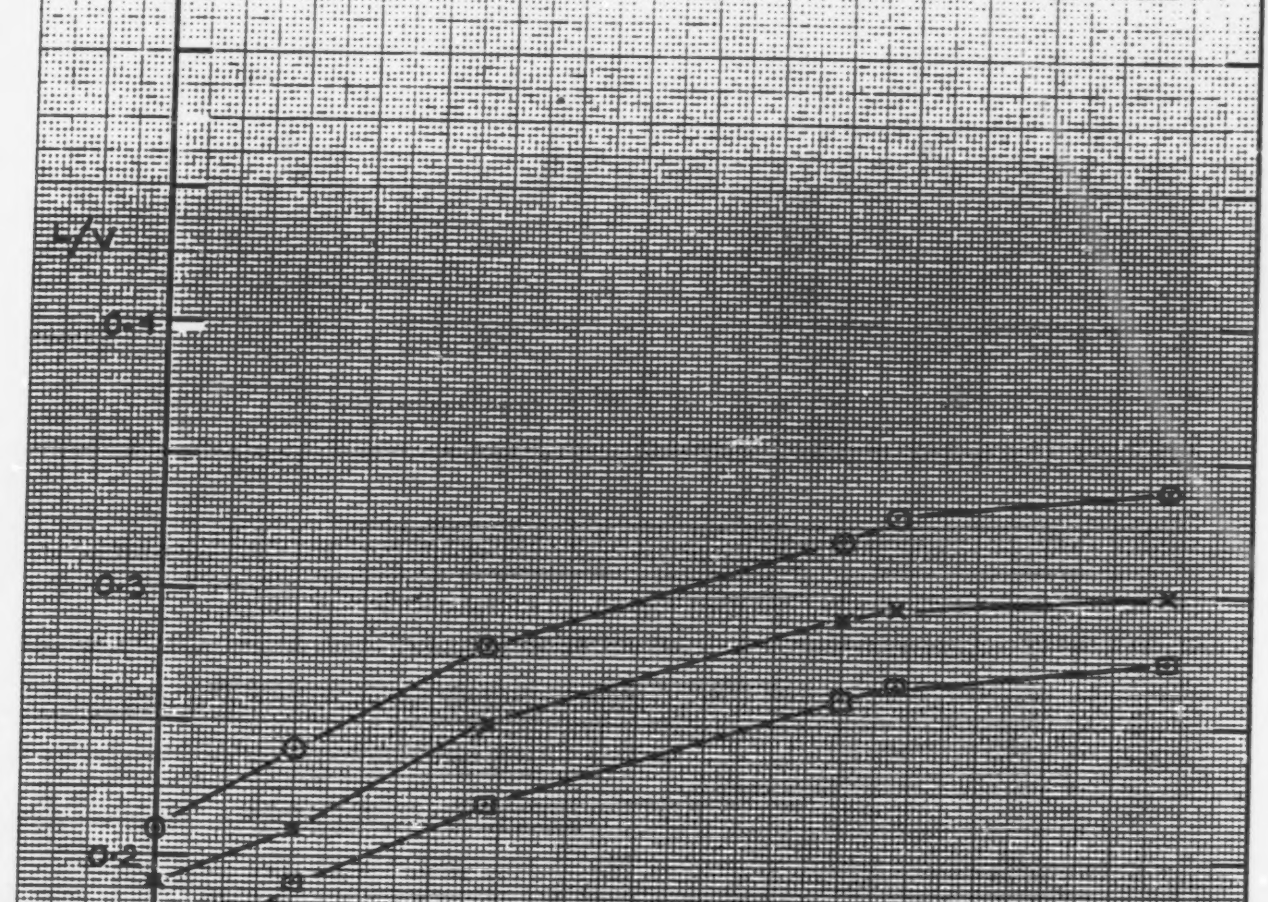


FIG. 3.5 L/V RATIO (OUTER LEAD WHEEL)
: EMPTY VEHICLE

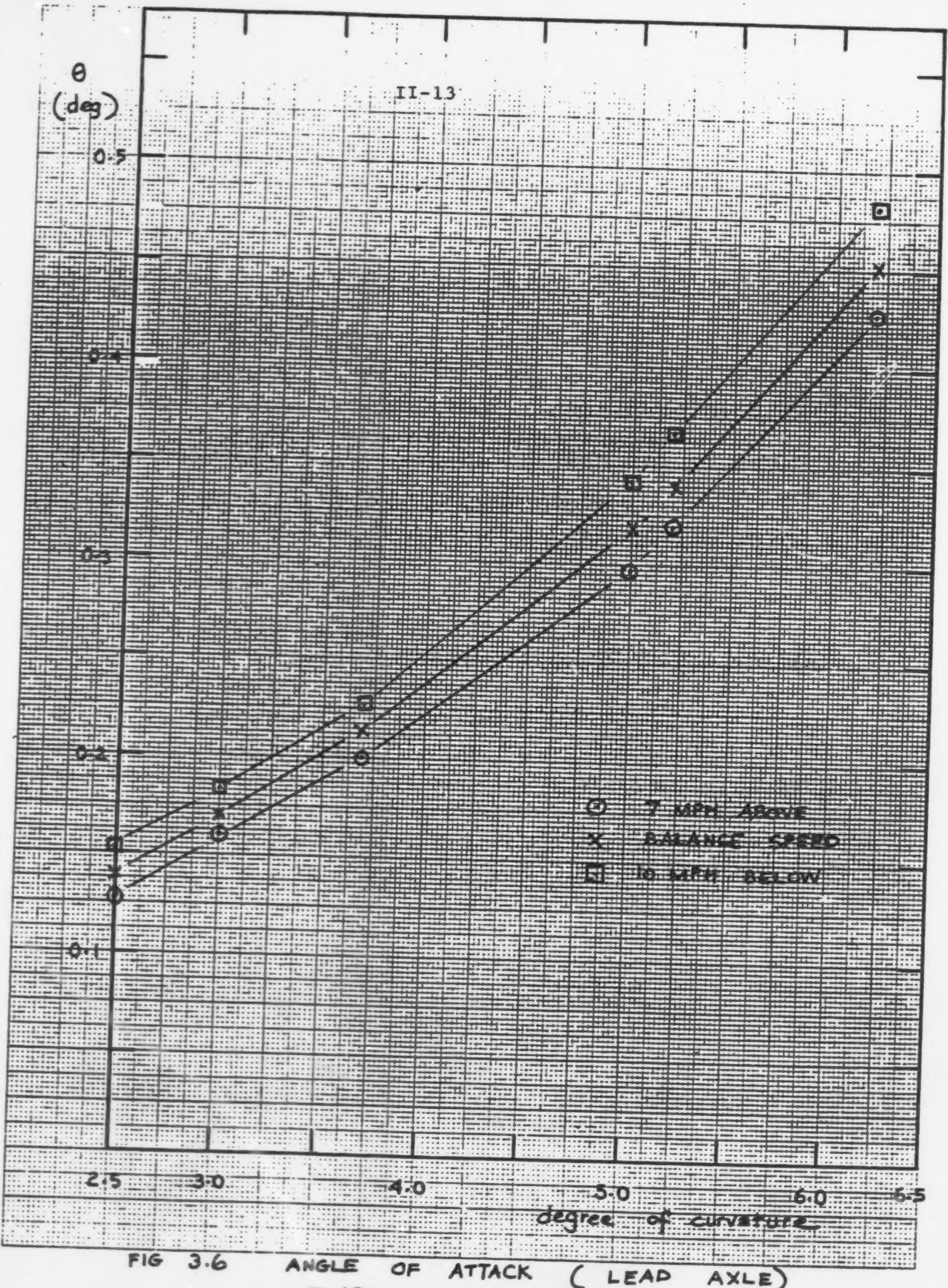


FIG 3.6 ANGLE OF ATTACK (LEAD AXLE)
: EMPTY VEHICLE

4.0 COMPARISON OF RESULTS FROM THEORETICAL AND EXPERIMENTAL METHODS

4.1 DIRECT QUANTITATIVE COMPARISON

Figures 4.1 and 4.2 show the comparison between the lateral force of the outer leading wheel as determined by experimental tests by Wyle Laboratories and as predicted by the curving analysis of section 3.

The experimental data are shown as points on the figures. The three points at each value of curvature correspond to the data measured at the three different test speeds. The theoretical data is plotted as three continuous lines and correspond to conditions of balance speed, 7 mph above, and 10 mph below the balance speed.

In general, it can be seen that the experimental results are higher than those predicted by the theoretical analysis. Although the experimental test speeds do not exactly correspond to those used in the simulation runs, this is not considered as being a significant item in terms of the observed differences.

Other sources of error which could explain these differences are as follows:

- Unusually high wheel/rail coefficient of friction during tests.

- The presence of asymmetric features of the truck-wheelset assembly. (The experimental data showed that some asymmetry might have existed during the tests: i.e. right hand curves were found to give larger forces than left hand curves).

- Incorrect assessment of the truck's stiffness properties.

- Incorrect assessment of the wheel/rail contact parameters.

- Errors in instrumentation or data processing (we cannot, however, make any assessment on the errors due to this item).

The effects of the first four of the above items are shown in section 5.

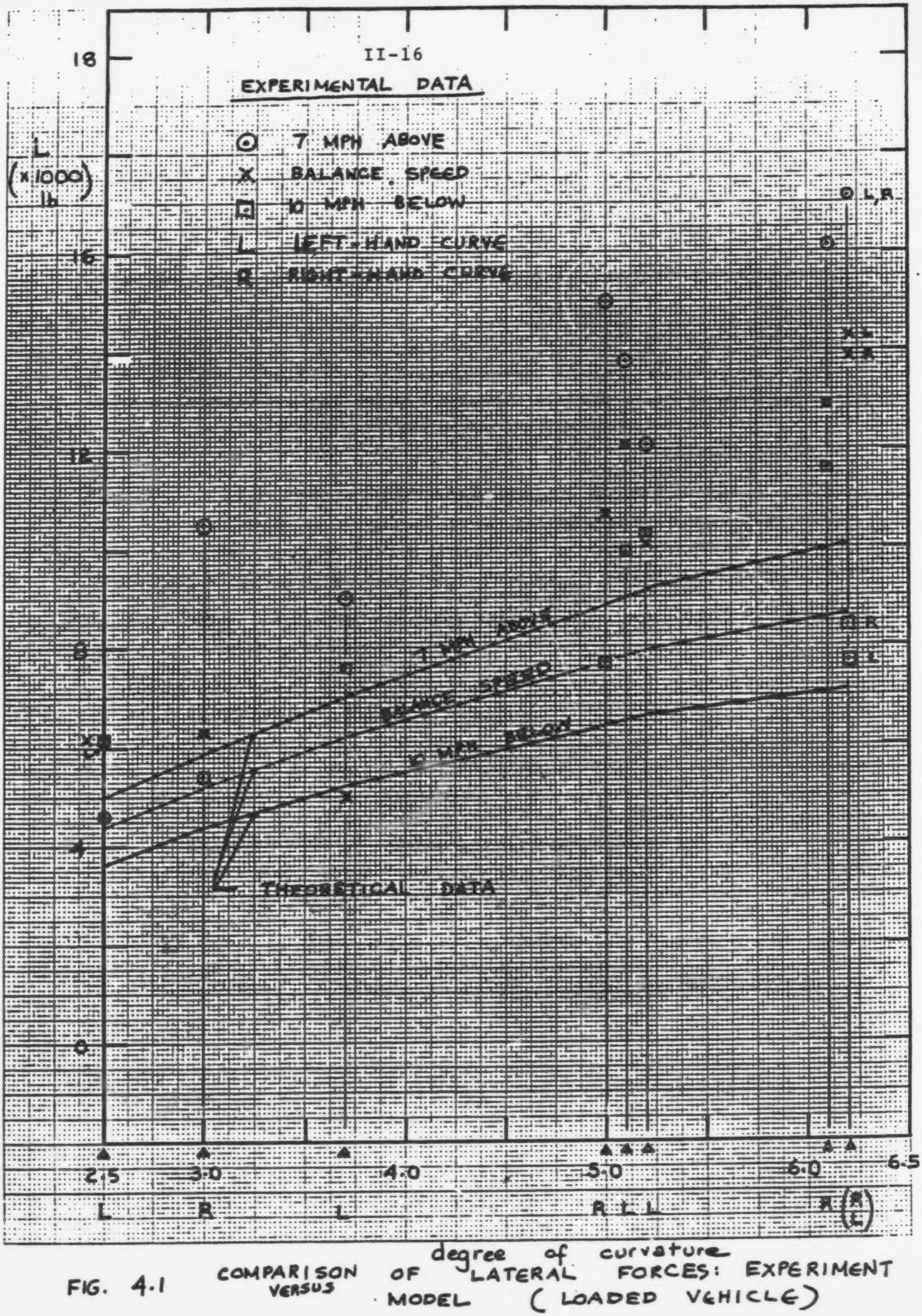
4.2 COMPARATIVE ANALYSIS OF THEORETICAL AND EXPERIMENTAL TRENDS

The curving model uses over fifty different input parameters. For the present analysis these parameters are classified into two groups.

i) Those that are considered as fixed parameters (e.g. wheel base, truck stiffnesses, etc.)
ii) Those that were varied during the tests and for which measured data was available.

This second category includes track curvature, superelevation and vehicle speed.

Correlation between theoretical and experimental results are only made on these three items. It is important to note



degree of curvature

FIG. 4.1 COMPARISON OF LATERAL FORCES: EXPERIMENT VERSUS MODEL (LOADED VEHICLE)

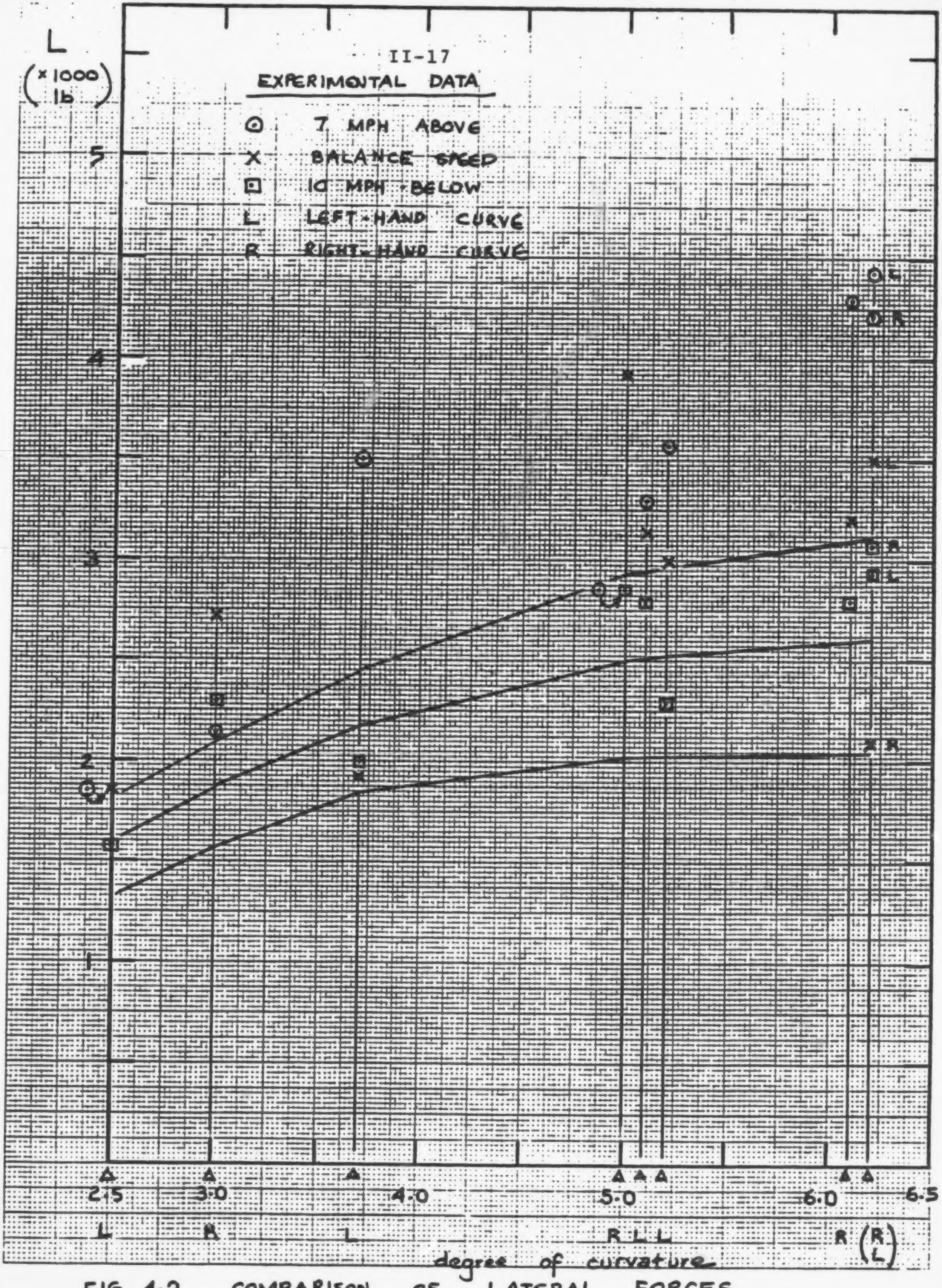


FIG. 4.2 COMPARISON OF LATERAL FORCES
: EXPERIMENT VERSUS MODEL
: EMPTY VEHICLE

that data for many of the parameters of the actual hardware tested were not available, and that engineering estimates were used to determine their values. In addition, it should be noted that the parameter values were selected prior to the examination of the experimental results.

EFFECT OF TRACK CURVATURE

Comparisons between the theoretical and experimental curving forces were made for the case of the loaded car at balance speed. Linear interpolation of the test data was sometimes required to obtain experimental curving forces since during the actual tests, the speeds occasionally were different from the desired balance speeds. Comparative results are shown in Figure 4.3 for the nine test curves.

It can be seen that the model and the experiments both predict a general increase in the lateral force of the leading outer wheel with an increase in track curvature. The model, however, predicts somewhat lower force levels than the test data.

EFFECT OF SUPERELEVATION AND SPEED

The effect of superelevation and speed can be studied using a single parameter defined as superelevation deficiency S_D[1] where:

$$S_D = S_V - S_A$$

---

[1] This assumes that the creep force characteristics can be normalized with respect to the vehicle's speed.

where: S_D = superelevation deficiency

S_V = theoretically required superelevation to exactly compensate the centrifugal acceleration

S_A = actual superelevation

The correlation between lateral curving force and superelevation deficiency was determined for both the theoretical and experimental data.

Defining the "Force Ratio" R_F (for the leading outer wheel only) as follows:

$$R_F = \frac{F_V}{F_B}$$

where: F_V = Measured lateral force for a given value of superelevation deficiency,

F_B = Measured lateral force at the balance speed (sometimes determined by linear interpolation of data at the three test speeds),

the effect of speed and superelevation can be found.

Figure 4.4 shows the graph of R_F versus S_D for the theoretical and experimental results. The latter is given as plots of the 27 individual points of the experimental data and by a plot of the least-square fit through these points. Both the theoretical and experimental results show an increase in the force ratio F_R with superelevation deficiency. The figure also shows that the mean slopes of the theoretical and experimental data are closely matched (0.085 for the former and 0.094 for the latter).

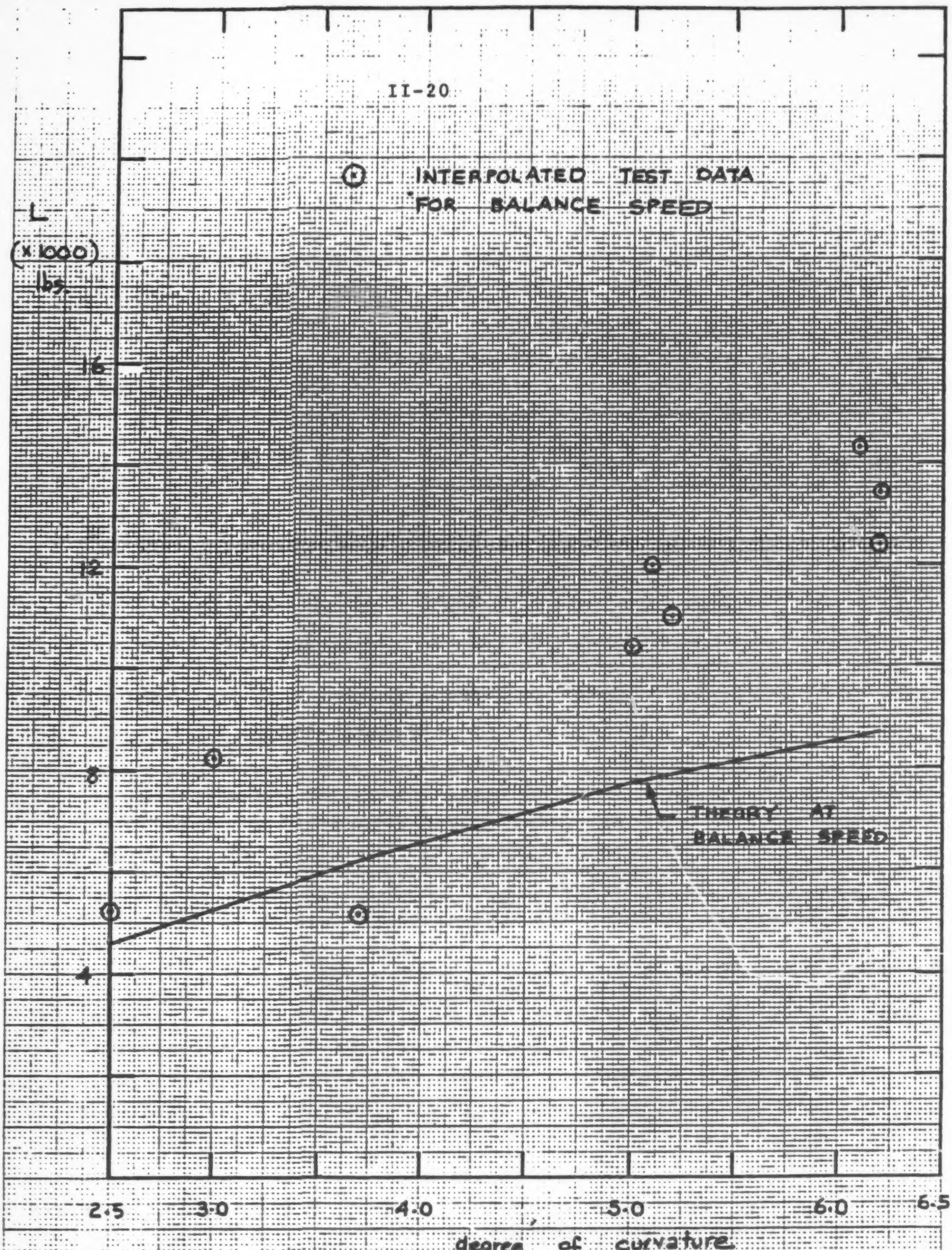


FIG. 4.3 EFFECT OF CURVATURE ON LATERAL FORCE (OUTER LEAD WHEEL)
: THEORETICAL AND EXPERIMENTAL RESULTS

10 X 10 TO THE INCH • 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 0703

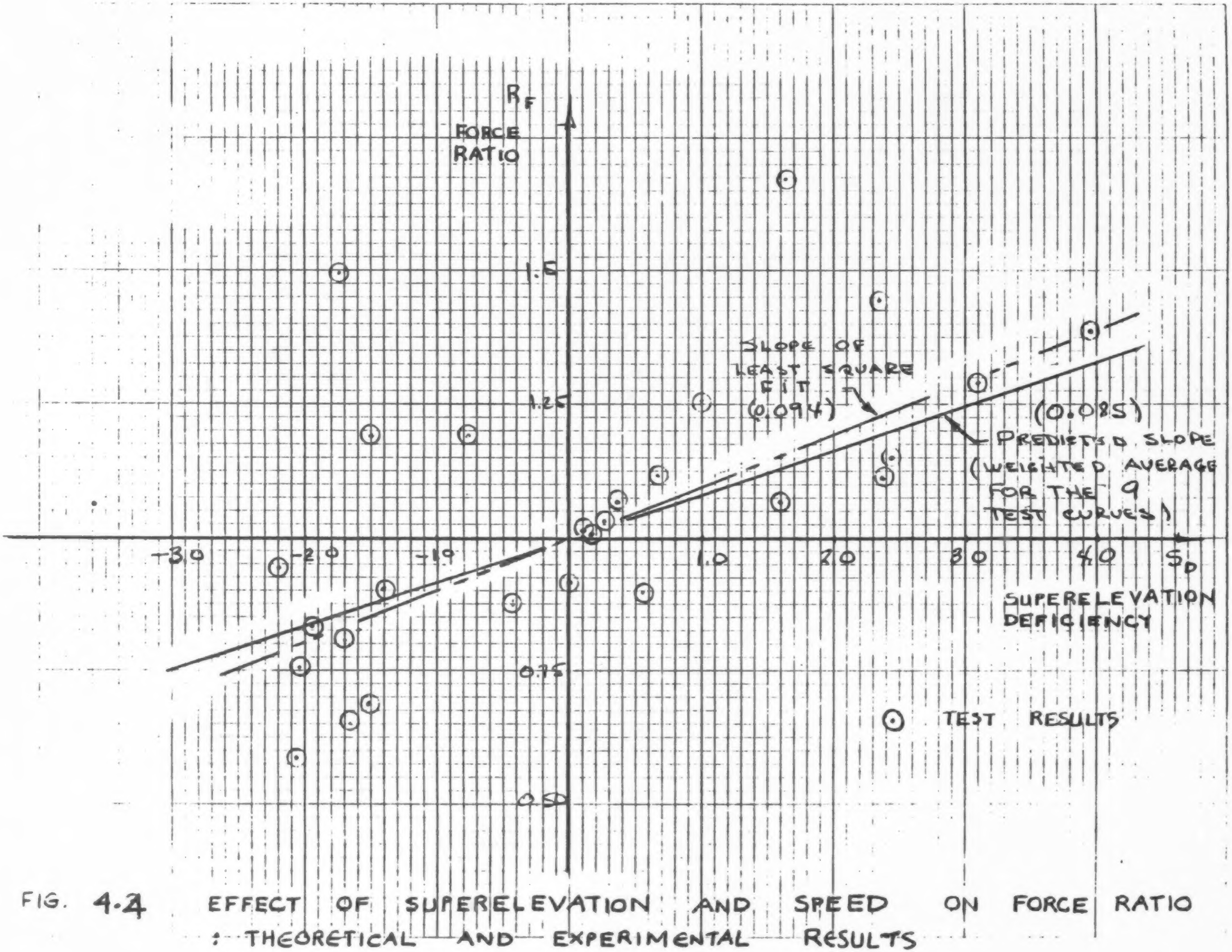


FIG. 4.4 EFFECT OF SUPERELEVATION AND SPEED ON FORCE RATIO : THEORETICAL AND EXPERIMENTAL RESULTS

5.0 PARAMETER SENSITIVITY ANALYSIS

An analysis was made to determine the sensitivity of the three measures of performance to a selected number of input parameters. The parameters chosen were as follows:

1. Coefficient of friction between the wheel and rail.
2. Diameter mismatch between outer and inner wheels of the wheelsets.
3. Parallelogramming stiffness.
4. Wheel profile parameters so as to model the effect of the CN Heumann profile which was later used on the type II truck tests).

Except for variations of the parameters listed above, values for all the parameters were taken to be the same as for the baseline vehicle (that is, the loaded 100 ton hopper car with type I trucks).

For the first three sensitivity parameters, the simulation runs were made at the balance speed of the six curves. For the wheel profile parameters, the runs were conducted at the three speeds for each of the six curves (at balance speed, 7 mph above and 10 mph below the balance speed).

COEFFICIENT OF FRICTION

Three values for the coefficient of friction between the wheel and rail were selected. These values were 0.15, 0.30 and 0.45 which represent low, normal and high values of the coefficient of friction which might be found in typical railway service.

Figures 5.1 and 5.2 show graphs of the lateral wheel/rail force and L/V ratio of the outer leading wheel versus curvature. It is seen that increasing the coefficient of friction increases both these measures of performance. In addition, for the case of $\mu = 0.15$, the value of the L/V ratio tends to saturate to a value approximately equal to the coefficient of friction.

WHEEL DIAMETER MISMATCH

Simulation runs were made for 5 conditions of wheel diameter mismatch between the outer and inner wheels of the wheelsets. The wheel diameters on the same side of the truck, however, were set equal (that is, there was no longitudinal mismatch of wheels). The four conditions correspond to the outer wheels being:

- 3 tape sizes larger(1)
- 1 tape size larger
- 0 tape size larger (i.e. no mismatch)
- 1 tape size smaller
- 3 tape sizes smaller

as compared to the inner wheels.

From figure 5.3, it can be seen that for low curvatures (less than 5°), there was a large effect on the lateral wheel/rail force of the leading outer wheel. At higher curvatures (greater than 5°), the effect was not as significant. Positive values of wheel mismatch (that is, wheelsets having larger outer wheel diameters as compared to the inner wheels) lower the lateral forces, whereas negative values increase the lateral forces.

---

(1) The "tape size" designation is a conventional railway term to measure wheel mismatch. One tape size is equivalent to .020 inch difference in rolling radius.

Figure 5.4 shows the influence of wheel mismatch on angle of attack. It can be seen that positive mismatch decreases the angle of attack, while negative mismatch increases the angle of attack. However, the negative values produced much larger changes in the angle as compared to the positive values.

PARALLELOGRAMMING STIFFNESS

Four values of parallelogramming stiffness were used in the analysis:

500 lb/in
1170 lb/in (baseline vehicle)
2500 lb/in
5000 lb/in

Simulation runs were made at balance speed for the six curves. Data from these runs are in Appendix B. Figures 5.5 and 5.6 show the results for the lateral force and angle of attack versus parallelogramming stiffness k for the two extreme values of curvatures; that is, 2.5 and 6.2 degrees. (It should be noted that the scale factors for L and θ on the two graphs are the same so that easy comparison of the results can be made).

Examining the figures, the following observations can be made:

- At low curvature (i.e. 2.5^o) increasing the stiffness k reduces the lateral force of the leading axle, while increasing that of the trailing axle.
- At moderate curvature (i.e. 6.2^o) increasing k produces the opposite effect: the lead axle outer wheel force increases, while the trail axle's decreases.
- The angle of attack of the lead and trailing wheelsets decreased with k for both curvatures.
- In general, there were only small changes in lateral force and angle of attack as the stiffness was varied. The most significant effect was in the reduction of the lateral force of the trailing outer wheel at moderate curvatures.

WHEEL PROFILE PARAMETERS

Figure 5.7 shows cross-sectional views of a standard AAR 1/20 profiled wheel and a CN Heumann profiled wheel on a section of worn rail during flange contact(1). The difference between the contact geometries of the two profiles are given by the following parameters:

	parameter	#in listing	Value	
			(AAR 1/20)	(CN Heumann)
1.	rail top to flange contact level	11	0.32	0.28
2.	flange to tread contact (lateral)	15	1.38	1.50
3.	flange contact plane angle	31	62.5	40.0

Figures 5.8 and 5.9 show the results of lateral wheel/rail force and angle of attack versus curvature for the CN Heumann profile. A comparison between these figures and those for the standard AAR profile (figures 3.1 and 3.2) indicate that the trends for L and θ are the same for the two profiles. However, the values for the CN Heumann profile are somewhat lower(in the neighbourhood of 5 to 14%) for the same set of operating conditions.

The more significant effect of the CN Heumann profile is on the trailing axle of the truck. As seen in figure 5.10, the lateral force on the trailing outer wheel at balance speed is nearly zero for all values of curvature studied. The standard profile however produces relatively high lateral forces on this wheel for curvatures greater than 5 degrees.

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(1) Extract from "Improved Wheel Tread Profiles for Heavy Freight Vehicles" ASME Journal of Engineering for Industry, August 1980, Vol. 102.

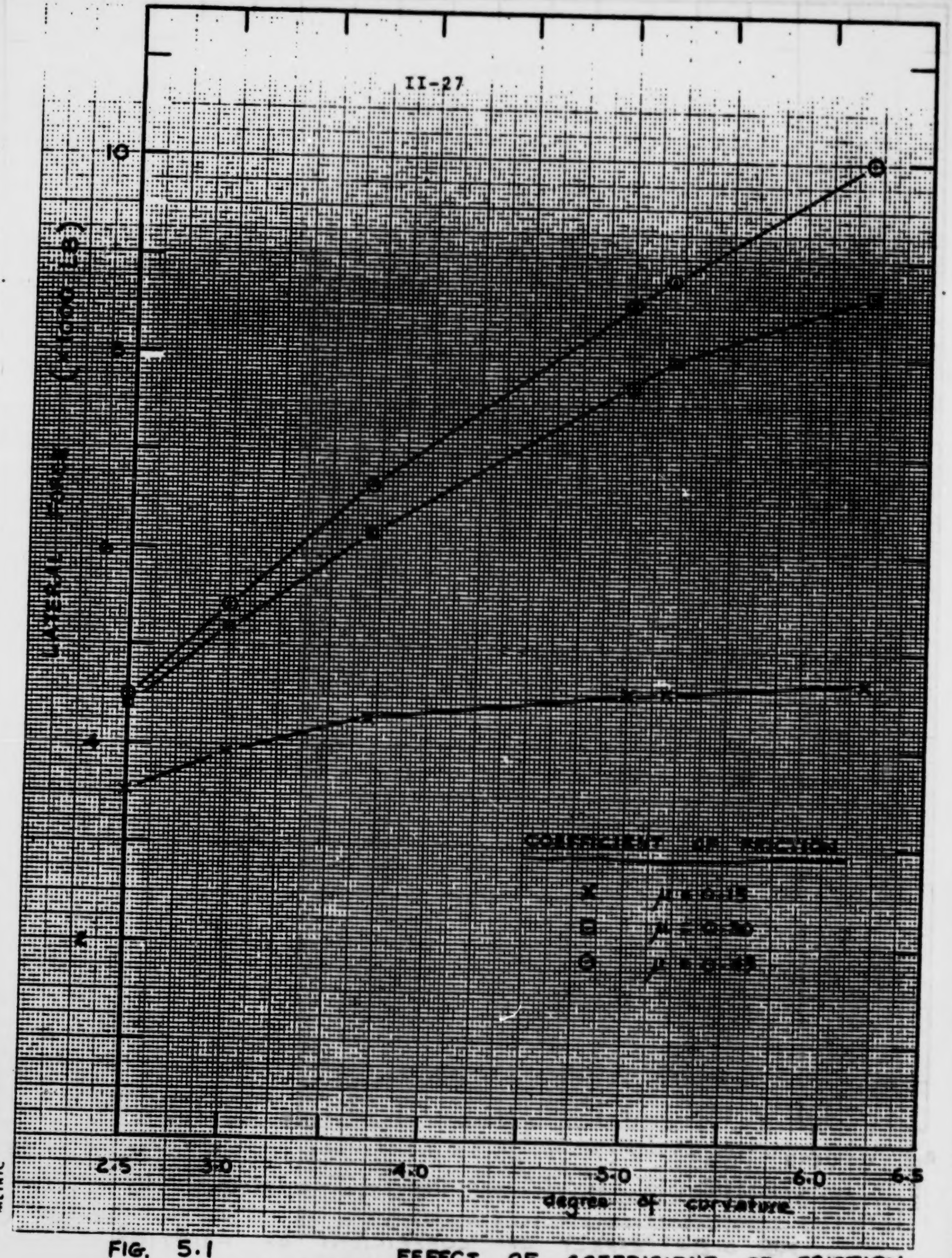

FIG. 5.1 EFFECT OF COEFFICIENT OF FRICTION ON LATERAL FORCE (OUTER LEAD WHEEL)

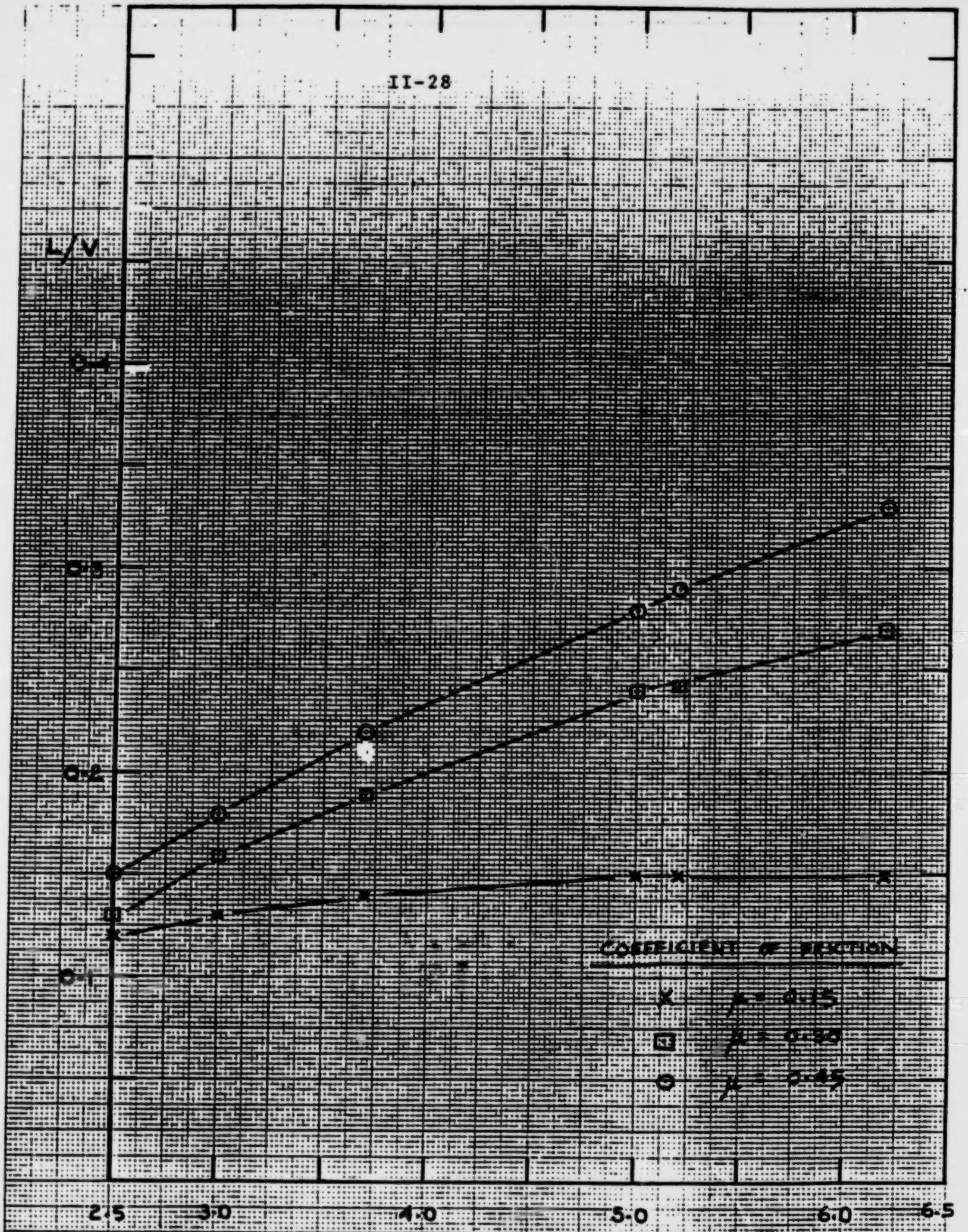

FIG. 5.2 EFFECT OF COEFFICIENT OF FRICTION ON L/V RATIO (OUTER LEAD WHEEL)

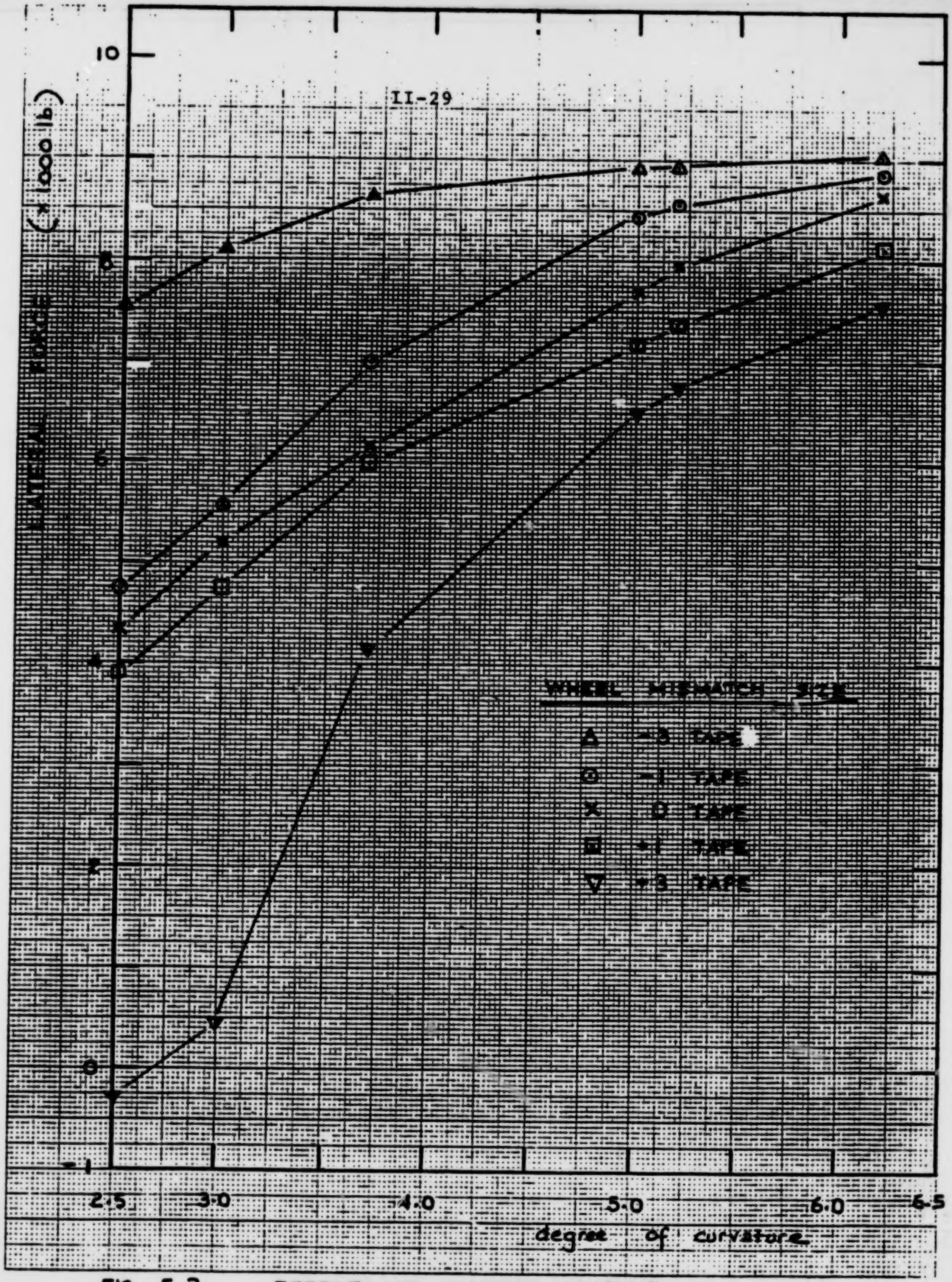

FIG. 5.3 EFFECT OF WHEEL MISMATCH ON LATERAL FORCE (OUTER LEAD WHEEL)

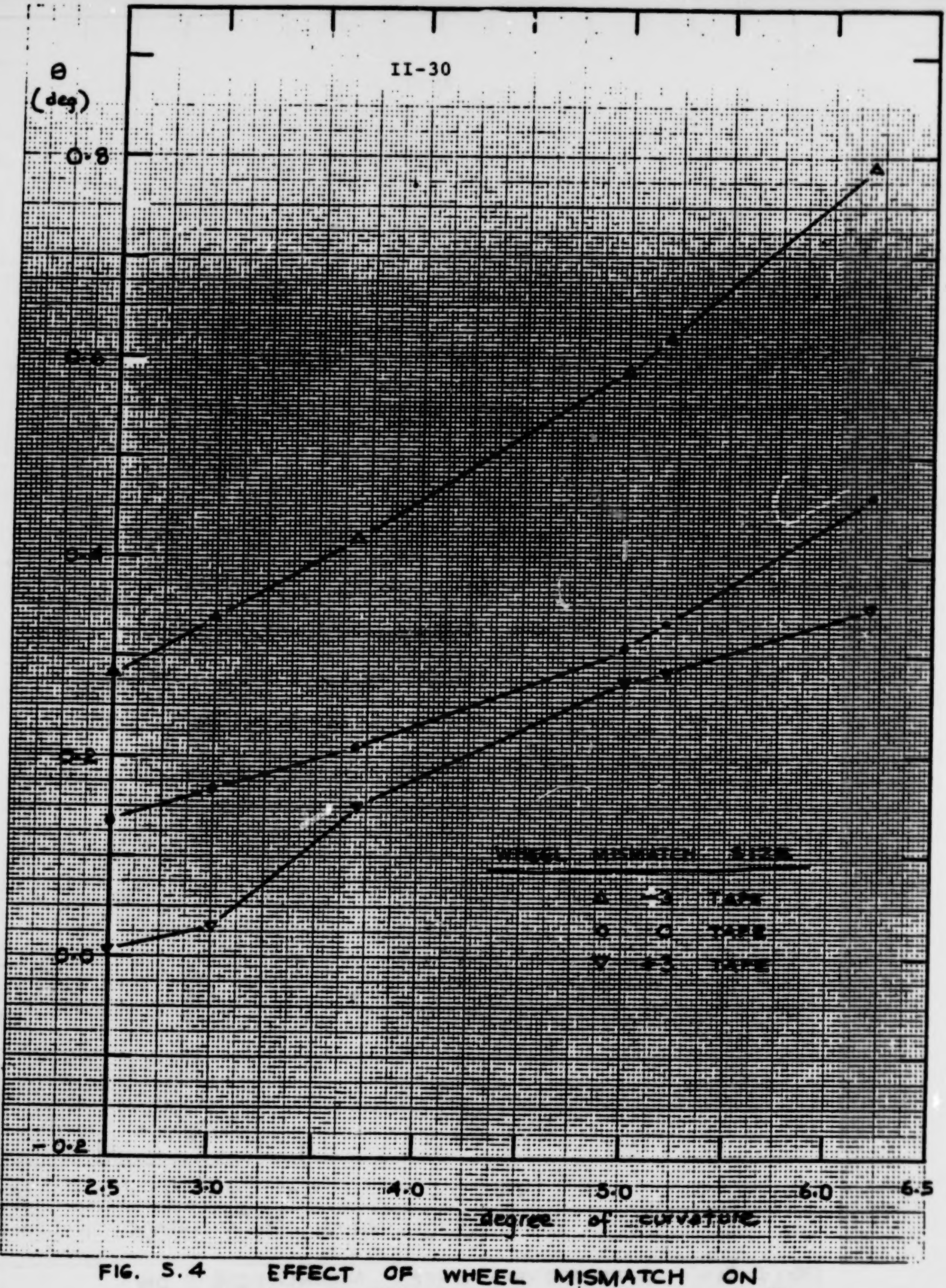

FIG. 5.4 EFFECT OF WHEEL MISMATCH ON ANGLE OF ATTACK (LEAD AXLE)

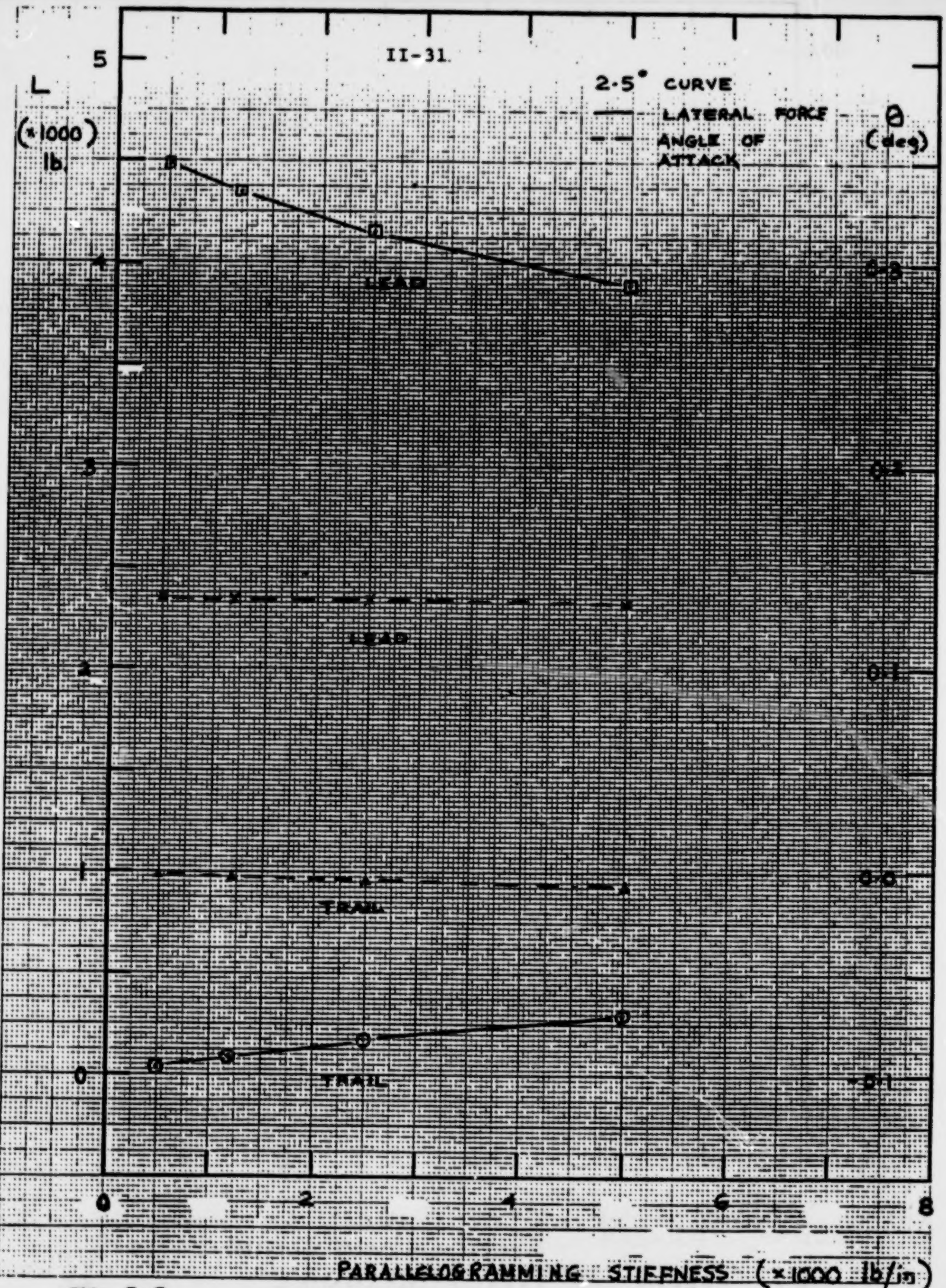

FIG. 5.5 EFFECT OF PARALLELOGRAMMING STIFFNESS ON LATERAL FORCE AND ANGLE OF ATTACK (2.5° CURVE)

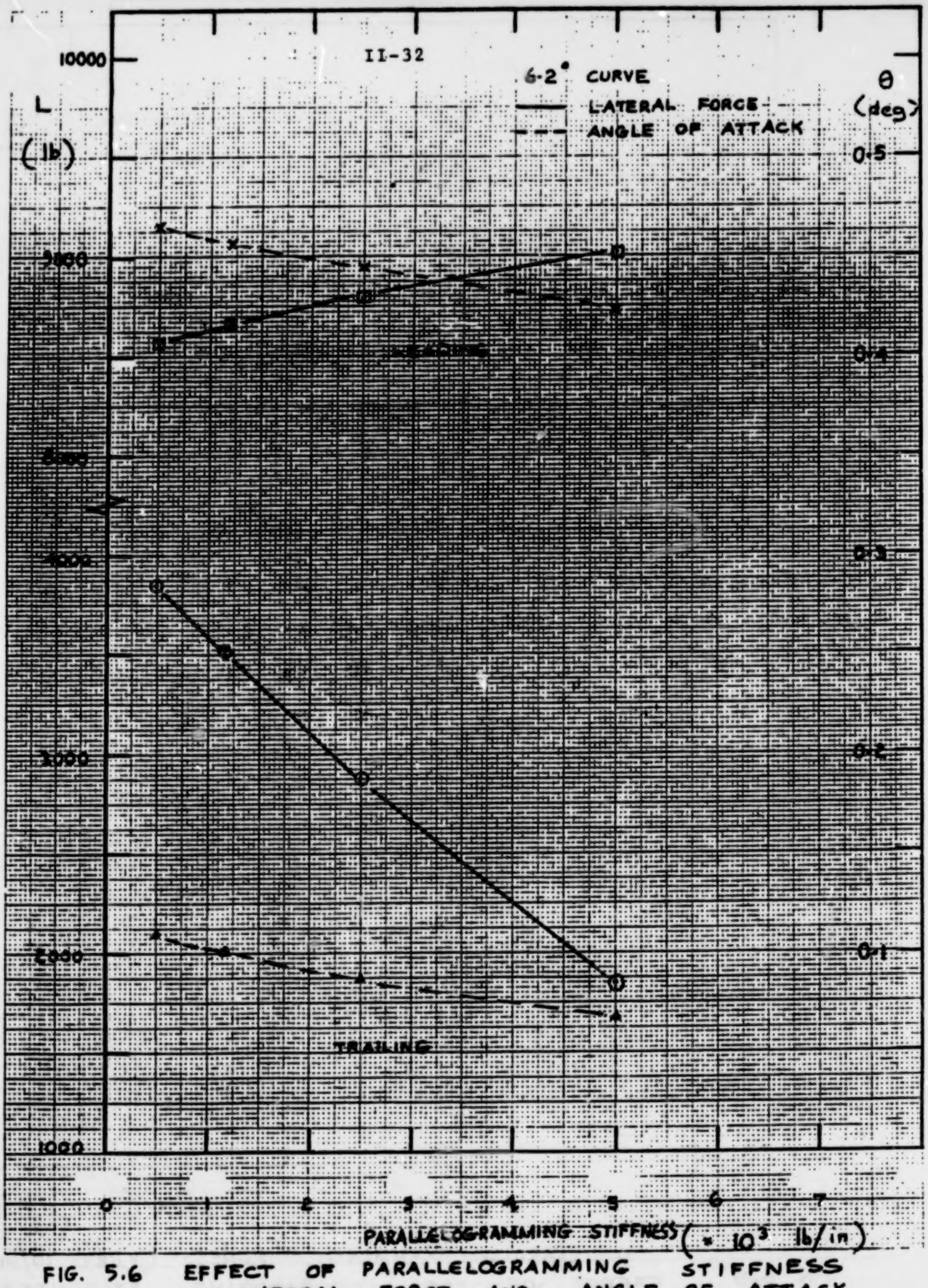

FIG. 5.6 EFFECT OF PARALLELOGRAMMING STIFFNESS ON LATERAL FORCE AND ANGLE OF ATTACK (6.2° CURVE)

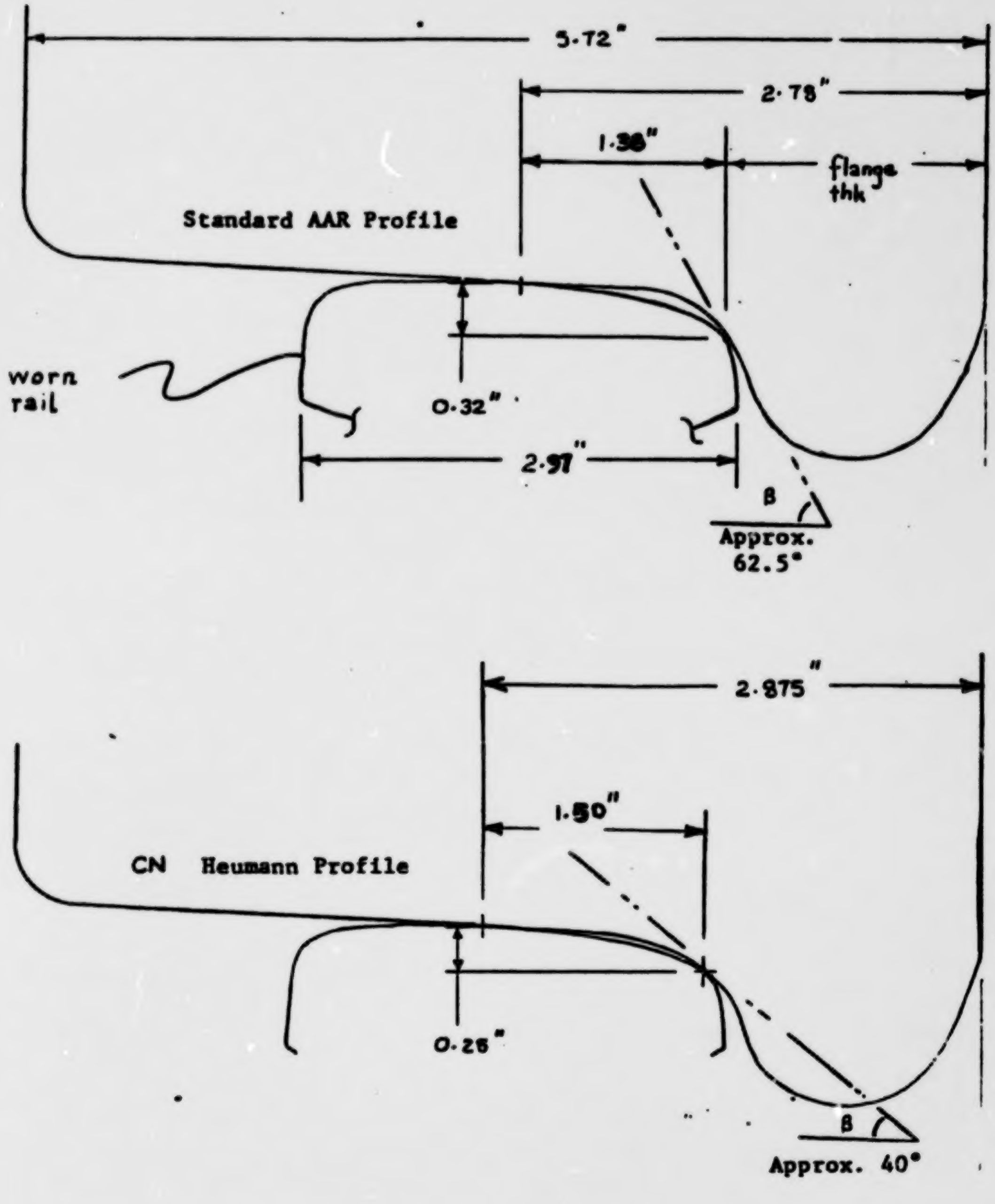
5.72"
2.78"
1.38"
flange thk
Standard AAR Profile
worn rail
0.32"
2.97"
β
Approx. 62.5°
2.875"
1.50"
CN Heumann Profile
0.25"
β
Approx. 40°

FIG. 5.7 CROSS-SECTIONAL VIEWS OF AAR STANDARD WHEEL PROFILE AND CN HEUMANN PROFILE ON WORN RAIL

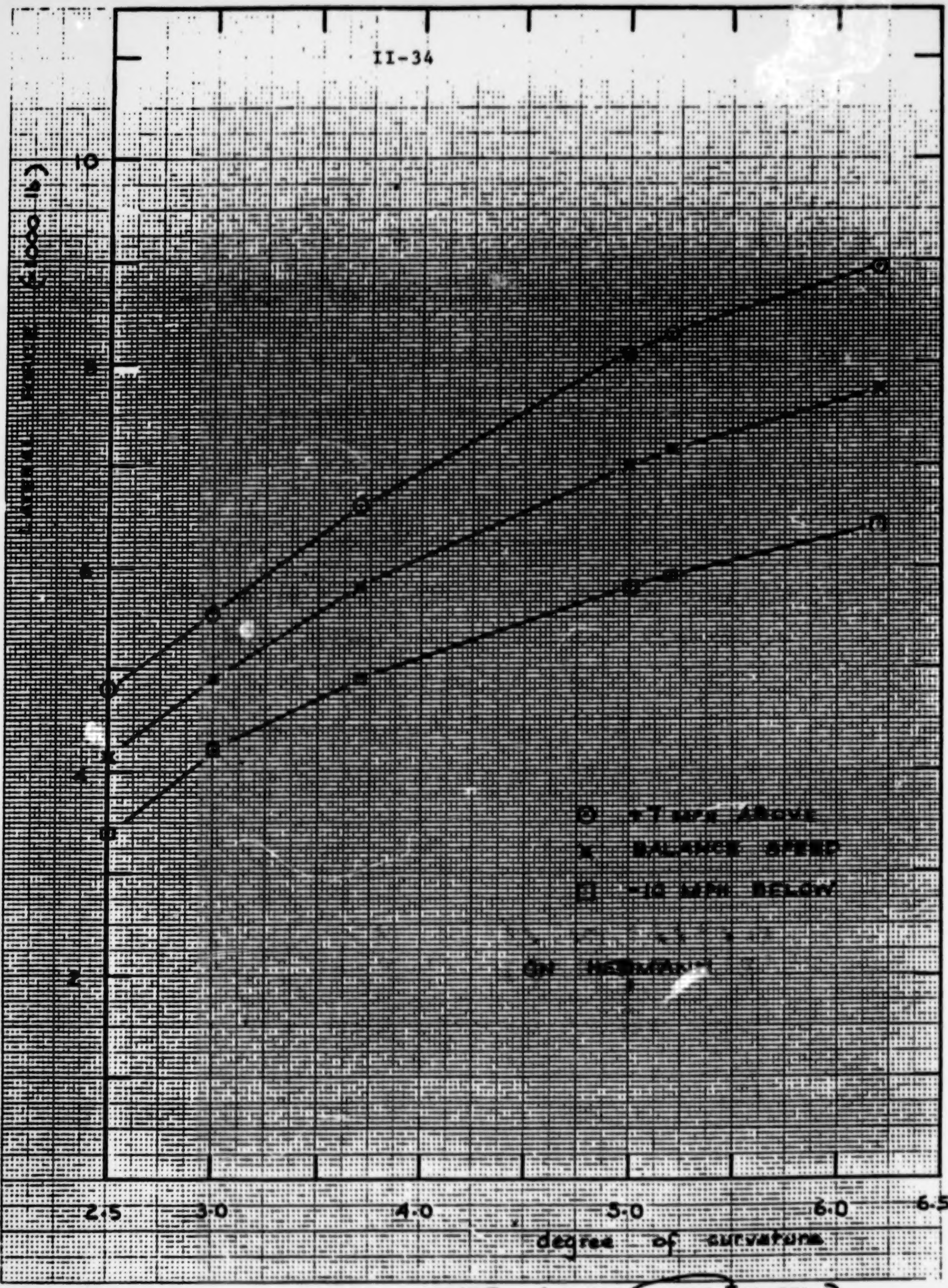

FIG. 5.8 LATERAL FORCE (LEAD OUTER WHEEL)
: CN HEUMANN PROFILE

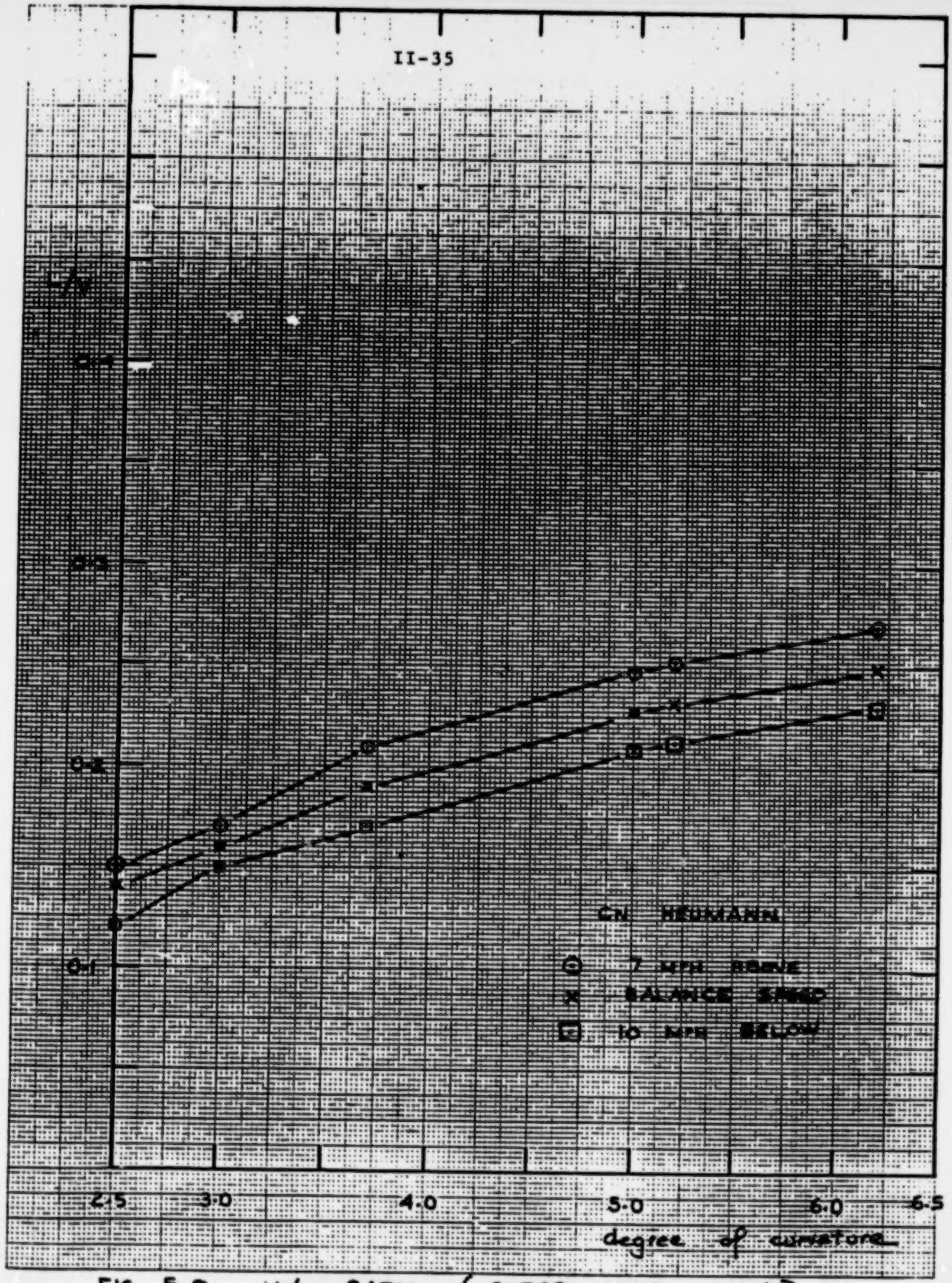

FIG. 5.9 L/V RATIO (OUTER LEAD WHEEL)
: CN HEUMANN PROFILE

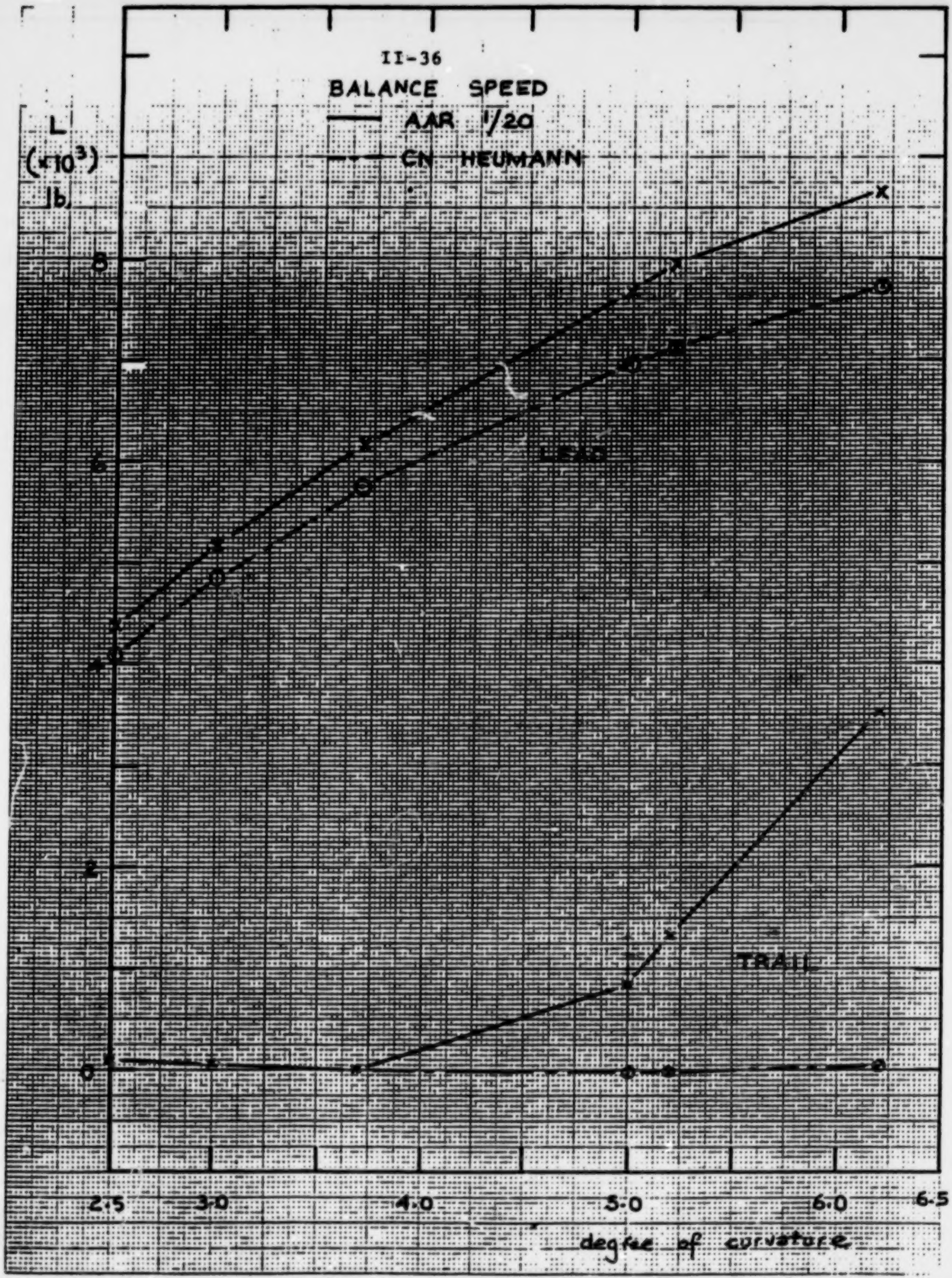

FIG. 5.10 COMPARISON OF LATERAL FORCES (OUTER LEAD AND TRAIL AXLES) : AAR 1/20 AND CN HEUMANN PROFILES

APPENDIX III

TYPE II TRUCKS STEADY-STATE CURVING ANALYSIS

1.0 INTRODUCTION

This report presents the results of analysis of the curving performance of the Type II freight car trucks as determined from a steady state mathematical curving model. A set of simulation runs using the model was performed which corresponded to experimental curving tests. The purpose of these studies was to provide technical assistance to Wyle Laboratories during the conduct of the TDOP project, as well as to establish the capabilities of the model to predict curving behaviour.

The report consists of four sections as follows:

- Approach to Type II Truck Curving Peformance Analyses.
- Model Input Parameters for Type II Truck Curving Analyses.
- Comparisons of Theoretical and Experimental Results for Steady State Curving.
- Parameter Sensitivity Analysis for Type II Trucks.

2.0 APPROACH TO TYPE II TRUCK CURVING PERFORMANCE ANALYSES

In the curving performance analyses of the type II freight car trucks, the approach taken for the simulations was similar to what was done for the type I truck curving analysis [1]. Namely:

1) To select a baseline set of parameters for each type II truck.

2) To perform a series of simulation runs for each truck corresponding to the experimental curving tests conducted by Wyle Laboratories for TDOP Phase II.

3) To compare the simulation and experimental results to find similarities in trends of performance between the two sets of results.

4) To perform various parameter sensitivity runs for each truck to show the influence of selected parameters on curving performance.

The values for the input parameters for each of the six baseline trucks(1) were selected using data supplied by Wyle Laboratories (for example: vehicle weight, truck dimensions). For data which was unknown (for example: truck stiffnesses) engineering estimates of the parameter values were made based on various assumptions which are discussed in section 3 of the report.

The curving performance of each truck under loaded and empty conditions, was determined using the theoretical model at four degrees of track curvature and at three vehicle speeds corresponding to 10 mph below, 7 mph above, and at the balance speed of each curve. The curve parameters used are given in Table 2.1. The values of track curvature and superelevation were the same as those used during the TDOP Phase II steady-state curving tests. The speeds corresponded to the intended vehicle speeds for the tests.

The output from the simulation runs of the type II trucks have the same format as the type I truck runs: that is, the lateral force and L/V ratio of the outer wheels of the leading and trailing wheelsets, and the angles of attack of the two wheelsets.

---

(1) In TDOP Phase II, seven type II trucks were tested. However, there was insufficient data on the functional operation and characteristics of the Alusuisse truck to be able to define a meaningful set of input parameters for this truck. As a result, no attempt at simulating the curving performance of the Alusuisse truck was made.

CURVATURE (deg)	SUPERELEVATION (in)	10 MPH BELOW BALANCE (mph)	BALANCE SPEED (mph)	7 MPH ABOVE BALANCE (mph)
2.5	4.09	38.5	48.5	55.5
3.7	3.72	28.1	38.1	45.1
5.1	4.88	27.0	37.0	44.0
6.2	4.98	24.0	34.0	41.0

TABLE 2.1 LIST OF OPERATING CONDITIONS

DISCUSSION ON THE APPROACH

The direct comparison of the results from the curving model against the TDOP test results represents a challenge because a wide range of simulated conditions are encountered. Indeed, the model must simultaneously consider a continuous range of track curvatures for six substantially different truck design configurations, at three different operating speed conditions, and for loaded and empty cars. An aspect which is critical in this task is that many of the detailed physical conditions present during the tests were not specifically measured.

Nevertheless, in order to proceed with the task in a manner as efficient and as scientific as possible, the approach described above was used. It should be noted that the complete set of parameters for all trucks were determined in advance, without prior study of the experimental test results. For parameters for which experimental data was not supplied, best engineering estimates were derived based on experience and available descriptions of the hardware. The simulations were then run for all trucks, and subsequently compared to the experimental test results. In addition, runs were performed to check the influence of various parameters whose values had been estimated in the simulation runs.

Obviously, the results obtained in this manner do not represent optimal matching between theoretical and experimental data. Rather, they represent a complete set of comparative data from which a perspective view of the analyses can be obtained with respect to parameter value estimations, predicted truck performances and comparative test results. At this stage we are in good position to assess where the predictions are best and where there is room for improvement. It is also an opportunity to discuss on a broader basis possible reasons for the observed discrepancies. Some points for discussion might include the experimentally observed differences between left and right hand curves, effects related to wheel and rail head profiles, as well as an error analysis on instrumentation and data processing methods. Upon completion of these discussions it will be possible to obtain a better assessment of the accuracy of the simulation models used in this project.

3.0 MODEL INPUT PARAMETERS FOR TYPE II TRUCK CURVING ANALYSES

3.1 CHARACTERIZATION OF THE WHEEL-RAIL INTERACTION

The wheel-rail characteristics used to simulate the Type II trucks are identical to those for the modified CN Heumann profile described in the interim report for the Type I Truck Simulations [1] , and a detailed description has not been repeated here. For convenience, however, a short description is given below.

A CN Heumann wheel profile in nominal new condition is assumed, based on the specification drawing supplied by Wyle Laboratories. Since no measured data on the rail head contours present during the tests was available, a sample worn rail head obtained from reference [4] was assumed. The Coulomb friction coefficient between wheel and rail was assumed constant at a value of 0.3 representing mean values on a sample mainline track, as given in reference [5] . Flangeway clearances were estimated based on nominal standard AAR wheelset mounting dimensions and the average track gauge which was measured using the track geometry recording car. Although manufacturing tolerances on wheel diameters are allowed within AAR standard practices, all wheels were assumed to have equal rolling radii.

3.2 CHARACTERIZATION OF TYPE II TRUCK CONFIGURATIONS

The following three configurations of freight car trucks have been studied in this project:

i) Rigid frame truck (i.e. having a single piece H-frame).
ii) Non-rigid frame truck (i.e. having a three piece construction).
iii) Rigid frame truck with a forced steering mechanism to the wheelsets.

In the "rigid frame" truck, the truck frame is assumed to be infinitely stiff. The wheelsets of the truck are elastically connected to the frame through lateral and longitudinal stiffness elements at the bearings. The Maxiride truck was studied using this configuration.

With respect to steady state curving, the difference between the "rigid frame" and "non-rigid" truck configurations is the mechanism by which the wheelsets of the trucks can move laterally (or parallelogram) with respect to each other. In rigid frame trucks, this occurs through elastic deformation of the lateral suspension at the bearings. For non-rigid frame trucks, the bearings of the wheelsets are restrained laterally to the side-frames and parallelogramming occurs as a result of the yaw flexibility between the truck bolster and the two sideframes. The lateral load path of the non-rigid frame truck is rigid and any lateral bolster force (due to superelevation deficiency) is shared equally between the two wheelsets.

The majority of the type II trucks were modelled using the "non-rigid frame" truck configuration (i.e. DR-1, Barber-Scheffel, Swing Motion, and ACF Fabricated). The differences in the characterization of these trucks were in (i) their component dimensions (though these differences were small), (ii) their stiffnesses in the longitudinal, yaw, and parallelogramming directions, and (iii) the maximum displacements associated with these stiffnesses prior to reaching the ends of travel of the suspension elements.

The third truck configuration corresponds to that of the Devine-Scales truck which essentially is a rigid H-frame truck having a wheelset steering mechanism. In this truck, the wheelsets are restrained laterally by the truck frame, and longitudinally by a linkage system connected to the frame and carbody. Whenever the vehicle is on a curve, the linkage tends to force the wheelsets into a radial position.

3.3 SELECTION OF MODEL INPUT PARAMETERS

The input parameters to the steady state curving model can be considered to be one of three types: carbody, wheel/rail interface, or truck parameters. Carbody parameters consist of truck spacing, wheel loads, height of the vehicle's centre of gravity, and height of the coupler (though this last item was not used in this project). Wheel/rail parameters consist of all items related to the track, the wheel geometry, and the adhesion characteristics. Flangeway clearance, wheel conicity, and the co-efficient of friction are examples of wheel/rail parameters. Truck parameters consist of primary suspension and truck stiffnesses, clearances within these stiffnesses, and truck dimensions.

The carbody parameters were selected to be the same as for the loaded and empty 100 ton hopper car data used in the type I truck steady state curving simulations [1] .

Values of the wheel/rail parameters were the same for all trucks, since in the TDOP test program, the same instrumented wheelsets were used on all trucks. The values correspond to those described in section 3.1.

The four type II non-rigid frame trucks were characterized by their stiffness values and clearances. Table 3.1 gives a comparison of the truck stiffnesses for these four trucks and the baseline truck from the type I studies.

The DR-1 and Scheffel trucks have reduced parallelogramming stiffness as compared to the type I truck due to the presence of the rubber pads at each bearing adapter. The primary function of these pads is to allow longitudinal compliance of the wheelset at each bearing with respect to the truck frame. For the DR-1, the pad is a single layer rubber element which was estimated to have a longitudinal stiffness of 15,000 lb/in [2] . The Scheffel truck uses multi-layer rubber pads at each bearing which are soft in the longitudinal direction. The net stiffness was estimated as being half that of the DR-1 truck (that is, 7500 lb/in). The DR-1 truck has cast steel steering arms which connect the two wheelsets together in the lateral direction. Their construction, however, permits some lateral motion between wheelsets due to structural elasticity. The inter-axle lateral stiffness of this truck design was estimated to be 36,000 lb/in[2]. The Scheffel truck has bolted wheelset adapters which are cross-connected by two pinned rods. The net inter-axle stiffness of the cross-bracing system was estimated at 9000 lb/in based on a simplified calculation of its structural stiffness.

TRUCK	LATERAL (PARALLELOGRAM) STIFFNESS: (lb/in)	LONGITUDINAL STIFFNESS (lb/in)	DIRECT INTER-AXLE STIFFNESS (lb/in)
TYPE I	1170	500×10^3	None
DR-1	500	15×10^3	36×10^3
BARBER-SCHEFFEL	500	7.5×10^3	9×10^3
SWING MOTION	500×10^3	500×10^3	None
ACF FABRICATED	500×10^3	30×10^3	None

TABLE 3.1 COMPARISON OF ESTIMATED STIFFNESSES FOR NON-RIGID FRAME TRUCKS

The Swing Motion, ACF and type I trucks all have rigid pedestals in the longitudinal direction and were estimated to have a stiffness of 500,000 lb/in. On the Swing Motion truck, these is a metal plate or "spring plank" which connects the two side-frames together to prevent parallelogramming. As a result, the lateral stiffness of this truck was selected to be very high (i.e. 500,000 lb/in). On the ACF truck there is also a metal plate which is used to resist parallelogramming. However, due to the presence of rubber rings surrounding the bearings on the truck, the lateral stiffness was decreased to 30,000 lb/in. Neither of these trucks have direct inter-axle connections; as a result, their inter-axle lateral stiffnesses were set to zero.

The only type II truck which was classified as having a "rigid frame" design was the Maxiride truck. The longitudinal and lateral stiffnesses prior to bottomming for this truck were set to be one third of the truck's vertical rate which is a realistic approximation for coil steel springs in shear. These stiffnesses are different for the empty and loaded vehicles because of the dual-rate springs used on this truck. For the loaded vehicle, the lateral rate was set at 14,000 lb/in per wheelset (that is, 7000 lb/in per bearing) over a working range of ± 1/2 inch, and the longitudinal rate at 7000 lb/in per bearing for ± 1/32 inch. The ± 1/32 inch longitudinal travel was used to simulate effects of fore-and-aft pedestal clearances. (Note: when either the longitudinal or lateral clearance is exceeded, the stiffness in that direction is assumed to be high: i.e. 500,000 lb/in).

The Scales truck also has a rigid single-piece frame. Laterally the wheelset connections to the frame are rigid and their stiffnesses were set to a high value (200,000 lb/in). Longitudinally the wheelsets are free to slide with respect to the frame, and a low value of stiffness (1000 lb/in) was used.

The truck has no inter-axle stiffness as there is no direct lateral inter-connections between wheelsets. The steering mechanism for the truck is shown schematically in figure 3.1. It consists of two symmetric linkages about the truck centreline with each linkage having a body link, a steering link and two axle links. In the simulation model the geometry of the mechanism is represented by the three distance variables A, B and C shown in the figure, and two stiffnesses K_1 and K_2. The values of these variables were set to:

$A = 39.5''$

$B = 57.0''$

$C = 1.75''$

$K_1 =$ 250,000 lb/in

$K_2 =$ 50,000 lb/in

These lengths are such as to provide ideal radial alignment when the vehicle is on a curve having a constant radius of curvature. The value of K_1 represents a stiff axle link, whereas K_2 represents a body link which is flexible. The selection of K_2 was calculated based on the bending stiffness of the carbody post which connects the body link to the carbody.

Appendix A gives the full list of the values of the input parameters for each of the six type II trucks in the loaded vehicle condition.

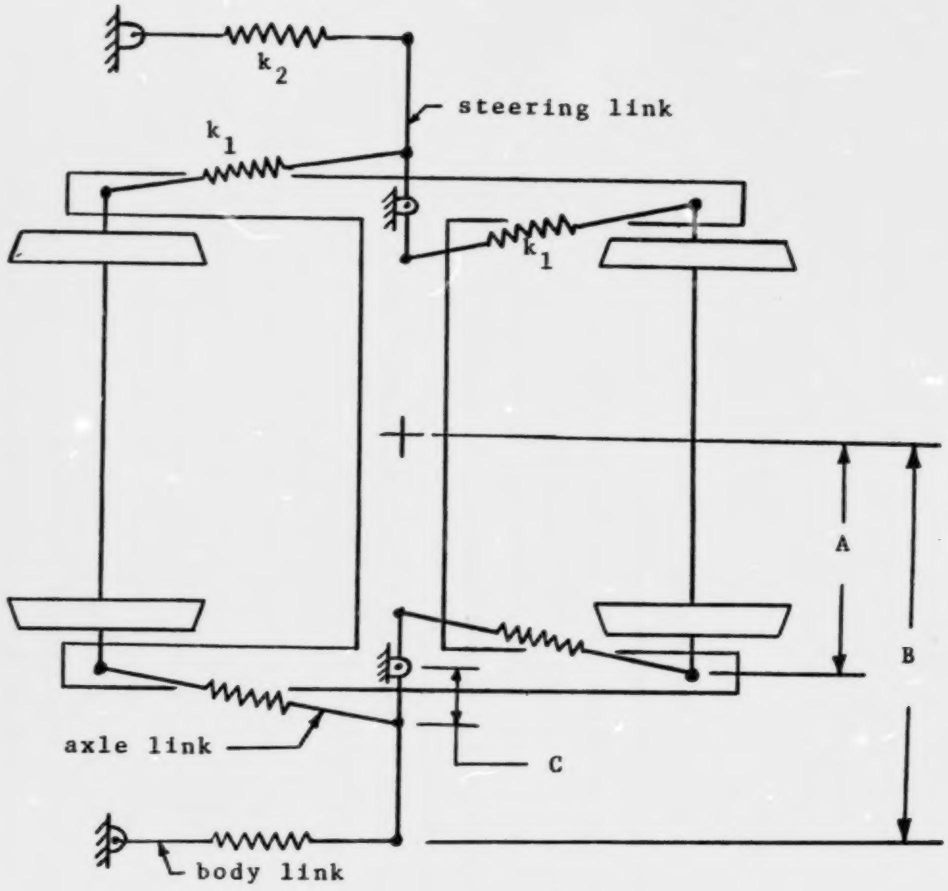
k
2
steering link
k
1
k
1
A
B
axle link
C
body link

FIG. 3.1 SCHEMATIC DIAGRAM OF SCALES TRUCK
AND REPRESENTATION OF MODEL INPUT PARAMETERS

4.0 COMPARISONS OF THEORETICAL AND EXPERIMENTAL RESULTS FOR STEADY STATE CURVING

4.1 DIRECT QUANTITATIVE COMPARISONS

The steady state curving performance of each Type II truck was studied at four values of track curvature, at three speeds on each curve, and in loaded and empty vehicle conditions. Appendix B[1] contains all of the computer output data from these runs (as well as those for the parameter sensitivity runs discussed in section 5 of this report). Appendix C[1] contains results of the lateral force on the leading outer wheel and the angle of attack of the leading wheelset. They are plotted directly onto the graphs of the test data so that a direct comparison of the theoretical and experimental results can be made. It should be noted that the same symbol notation as used by Wyle Laboratories in their TDOP Phase II Performance Specification Report [3] is adopted, except that an "S" has been added against the simulated data to distinguish it from the experimental results.

In general, the theoretical lateral forces and angles of attack for all trucks are found to be lower than those measured in the tests. The agreement between theoretical and experimental forces is generally the best on smaller degrees of curvature (2.5° and 3.7°) and for empty vehicle conditions. In particular, the results of the DR-1 and Scales trucks show quite a good match in the lateral forces for the empty condition. (It should be noted that no experimental results of lateral forces were available for the ACF Fabricated truck. However, for completeness, the theoretical results for this truck were also plotted).

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[1] Appendices B and C of the interim report have not been included.

The experimental values for angle of attack do not generally show good agreement with the simulation results. Whereas the simulation angles generally show small and linear variations with speed, there are often large variations in the experimental data. In some cases, however, there is a good match; for example, the DR-1 truck, empty condition, on 3.7 and 5.1 degree curves; and the Scales truck, empty condition, on 2.5 and 6.2 degree curves.

4.2 COMPARISON OF TRENDS

Comparisons between the theoretical and experimental results were made with respect to the sensitivity of the lateral force at the leading outer wheel to:

i) variations in track curvature.
ii) variations in vehicle speed.

(Note: because there was no data on the experimental forces for the ACF Fabricated truck, the following analysis was not performed on this truck).

EFFECT OF TRACK CURVATURE

a) Direct comparison of data

Comparisons between the theoretical and experimental lateral forces of the five Type II trucks at balance speed for the loaded and empty conditions are shown in figures 4.1 through 4.5. Linear interpolation of the test data was sometimes required to obtain the experimental force as during the tests, the actual vehicle speeds did not always correspond to the balance speeds of the curves.

Similar to what was found in section 4.1, the experimental results are higher than those found in the simulations except for two cases. These are (i) the DR-1 truck, empty condition, where the theoretical values were higher, and (ii) the Scales truck, empty condition, where the results of the two were nearly the same.

b) Comparison of Theoretical and Experimental Trends assuming a Linear Relationship between Force and Degree of Curvature

The theoretical data show that for the range of curvatures studied, there is a reasonably linear variation of lateral force with curvature for a given load condition. By doing a linear fit on both the theoretical and experimental data, one can obtain the comparative sensitivity of the lateral force with respect to track curvature, as measured by the rate of change in units of (lb/degree). The rates have been determined for the five trucks in loaded and empty conditions and are shown in Table 4.1. Comparisons of the rates shows reasonably close agreement between theoretical and experimental data for all trucks.

c) Comparison of relative truck ranking

A comparison between the simulation and test data was made with respect to the relative ranking of the Type II trucks, in terms of producing low lateral forces. Figures 4.6 and 4.7 are graphs of the lateral force versus curvature from the experimental and theoretical results respectively for the Type II trucks. It can be seen that both sets of results predict lower forces for steering type trucks (i.e. DR-1, Barber-Scheffel, and Devine-Scales) as compared to non-steering type trucks (i.e. Swing Motion, Maxiride, and ACF). Also, except for a reversal in rank between the DR-1 and Barber-Scheffel trucks, the theoretical model shows the same order of ranking as the experimental data.

TRUCK	RATE OF CHANGE (lb/deg) empty vehicle		RATE OF CHANGE (lb/deg) loaded vehicle	
	MODEL	TEST	MODEL	TEST
DR-1	600	300	1500	2000
BARBER-SCHEFFEL	400	800	1500	1600
DEVINE-SCALES	700	300	1400	1400
MAXIRIDE	400	500	1700	1800
SWING MOTION	500	400	1600	2300

TABLE 4.1 COMPARISON OF LATERAL FORCE VERSUS CURVATURE TRENDS: TYPE II TRUCKS

EFFECT OF VEHICLE SPEED

An analysis was performed on the sensitivity of the lateral force to variations in curving speed. The simulation data showed that there was a nearly linear relationship between lateral force and speed for a given track curvature. This was also found to occur in many cases for the experimental data.

Assuming such a linear relationship, we can determine the slope of the lateral force versus speed for both the theoretical and experimental data. Figures 4.8 through 4.12 show the graphs of the force-versus-speed slope plotted against track curvature for the five Type II trucks in loaded and empty conditions.

These graphs show that there is generally closer agreement between experimental and theoretical data for the cases of smaller degrees of track curvature (2.5^o and 3.7^o) and for empty vehicle conditions for the five trucks. The theoretical results show a gradual increase in the lateral force sensitivity as the degree of track curvature increased. The test data, however, shows a much higher sensitivity, particularly for the loaded trucks on the larger curvatures.

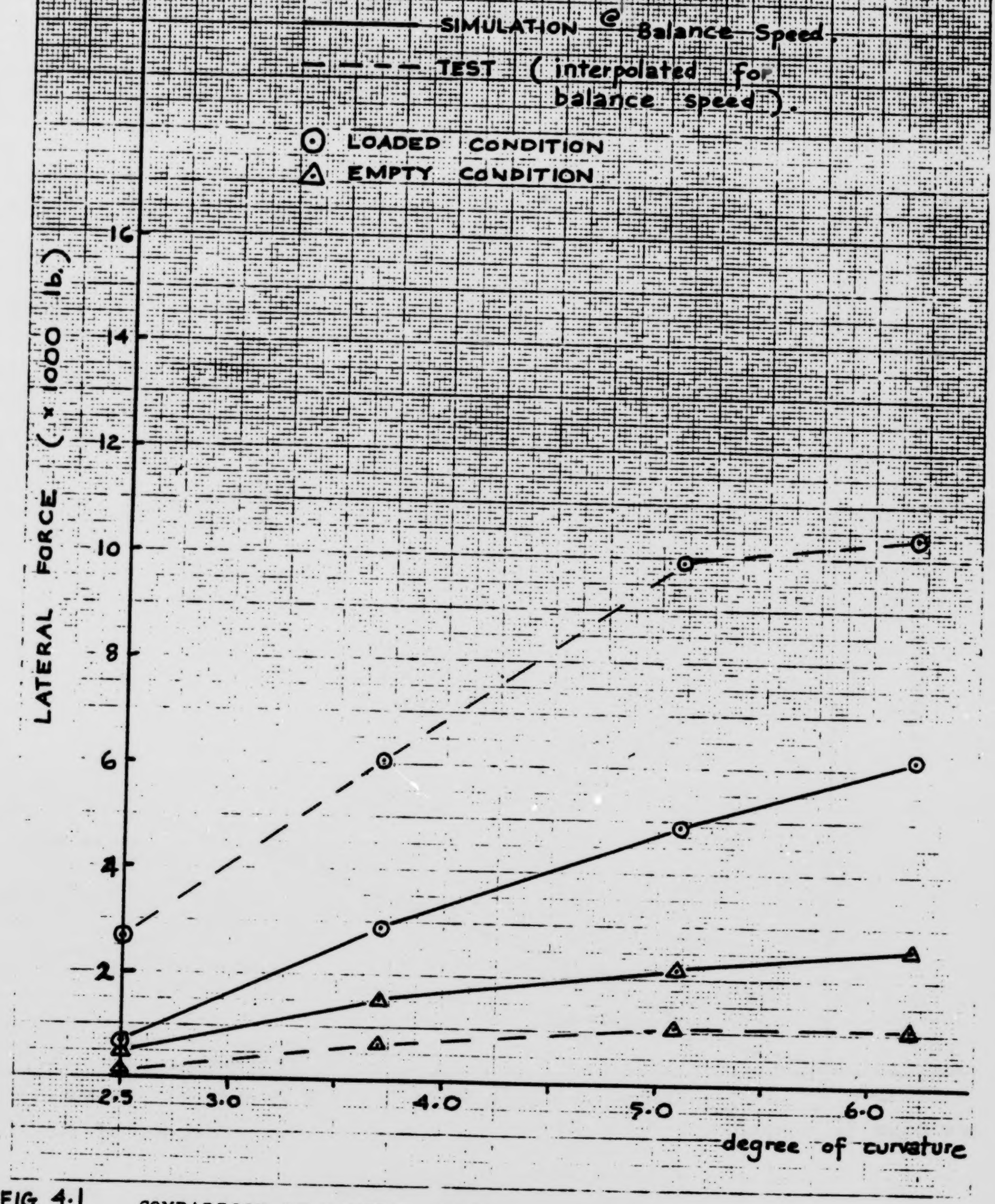

FIG. 4.1 COMPARISON OF LATERAL FORCE VERSUS CURVATURE: DR-1 TRUCK

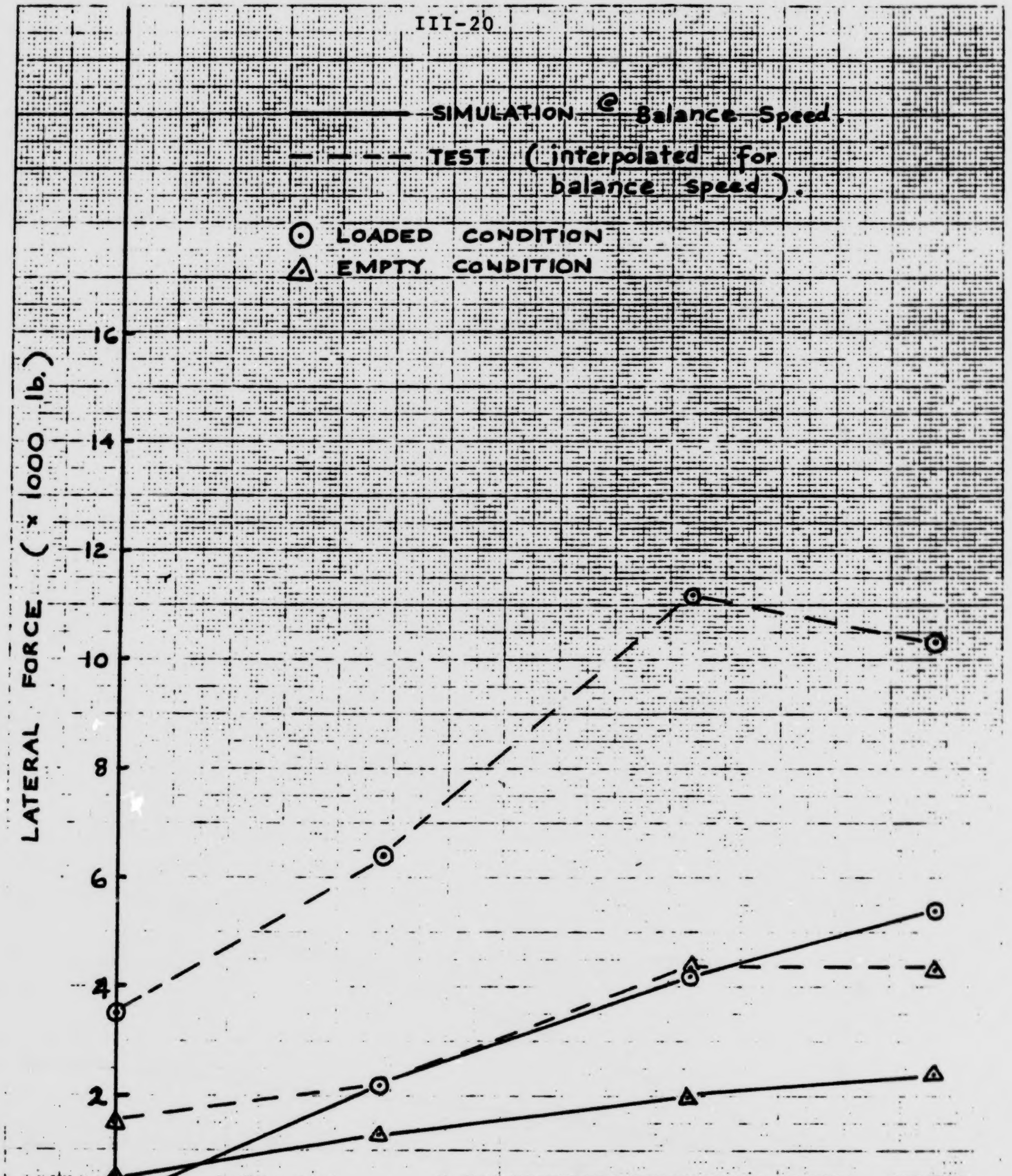

FIG 4.2 COMPARISON OF LATERAL FORCE
VERSUS CURVATURE: BARBER-SCHEFFEL TRUCK

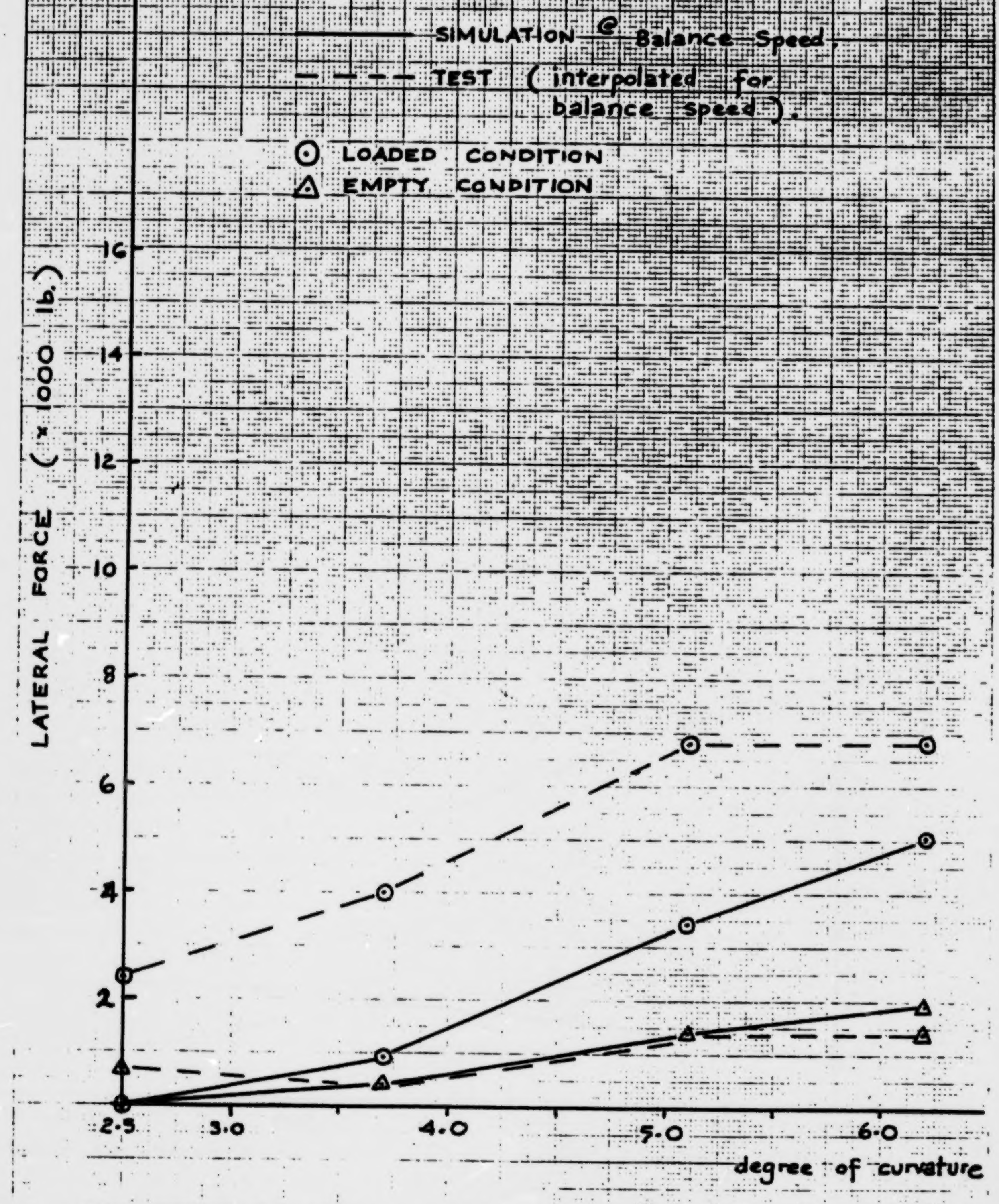

FIG 4.3 COMPARISON OF LATERAL FORCE VERSUS CURVATURE: DEVINE-SCALES TRUCK

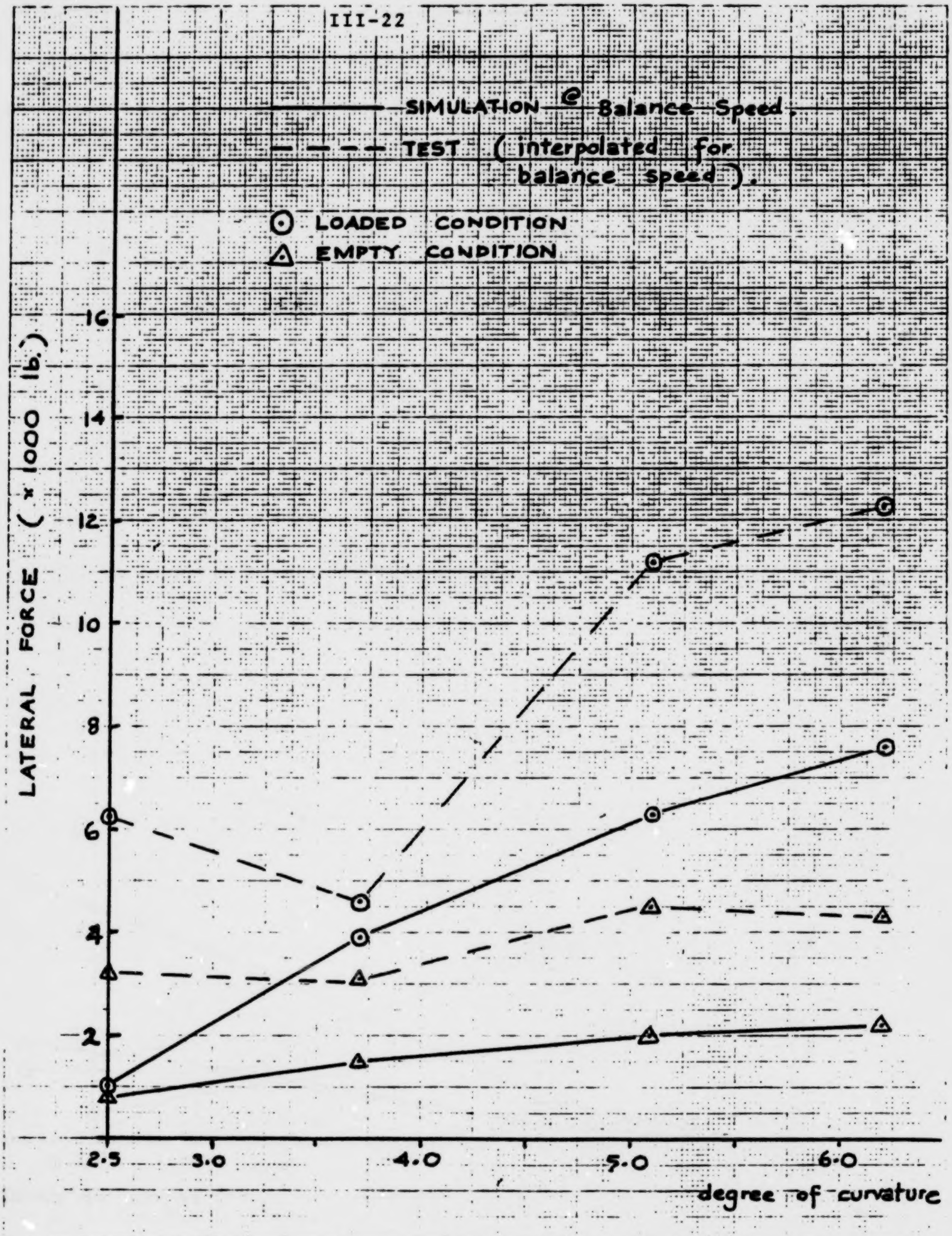

FIG 4.4 COMPARISON OF LATERAL FORCE VERSUS CURVATURE: MAXIRIDE TRUCK

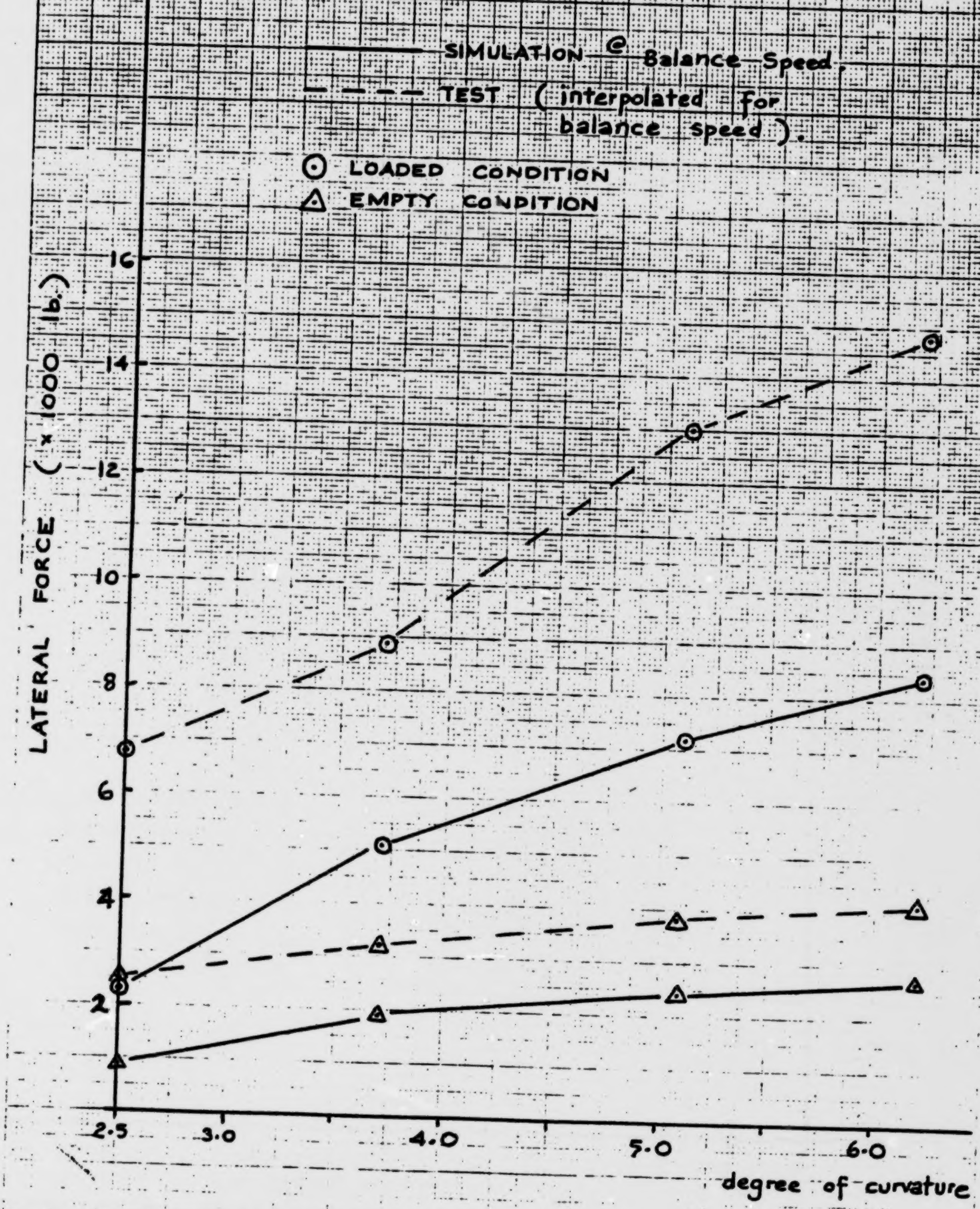

FIG 4.5 COMPARISON OF LATERAL FORCE VERSUS CURVATURE: SWING MOTION TRUCK

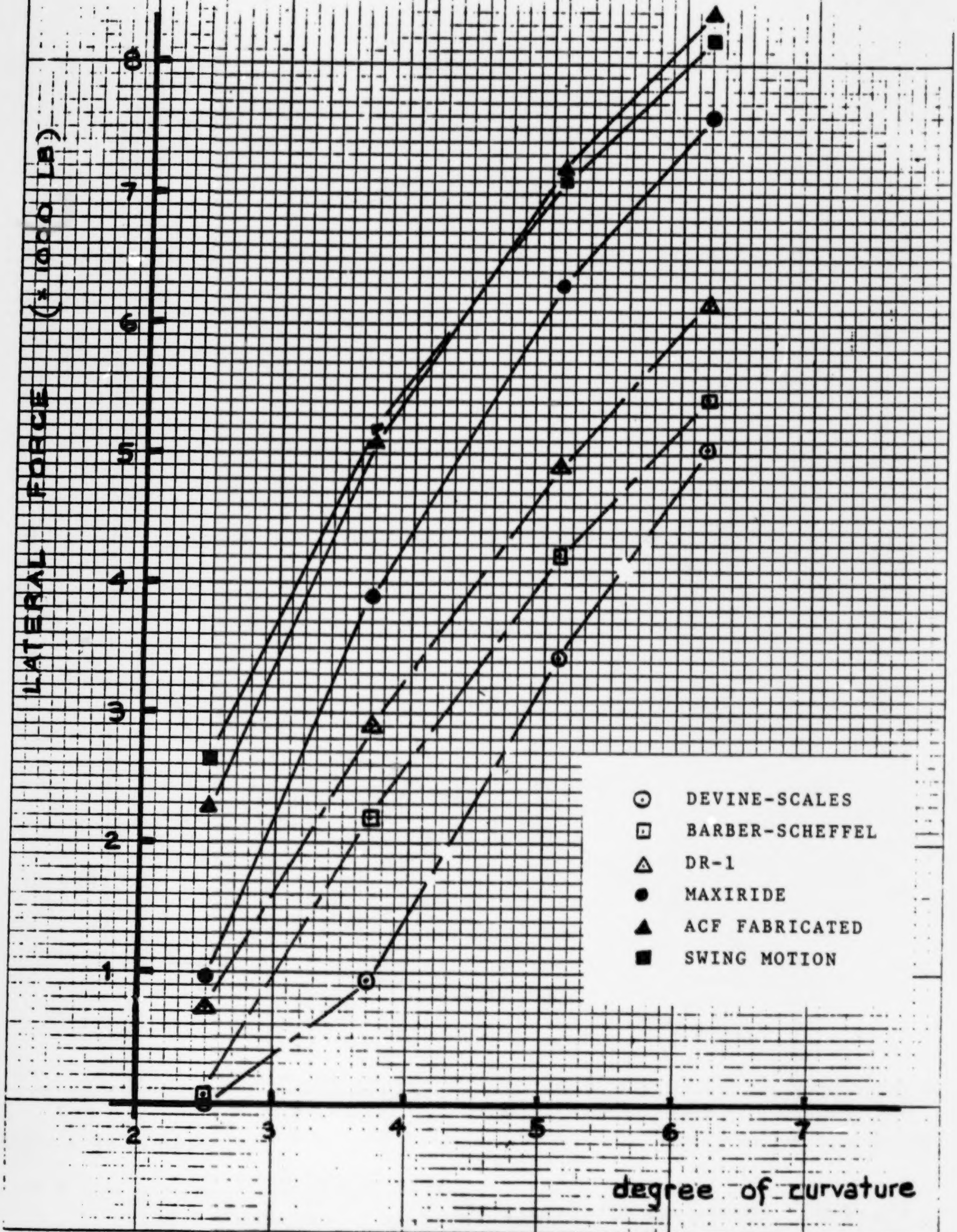

FIG.4.6 COMPARISON OF LATERAL FORCE VERSUS CURVATURE: ALL TRUCKS, LOADED CONDITION - THEORETICAL DATA

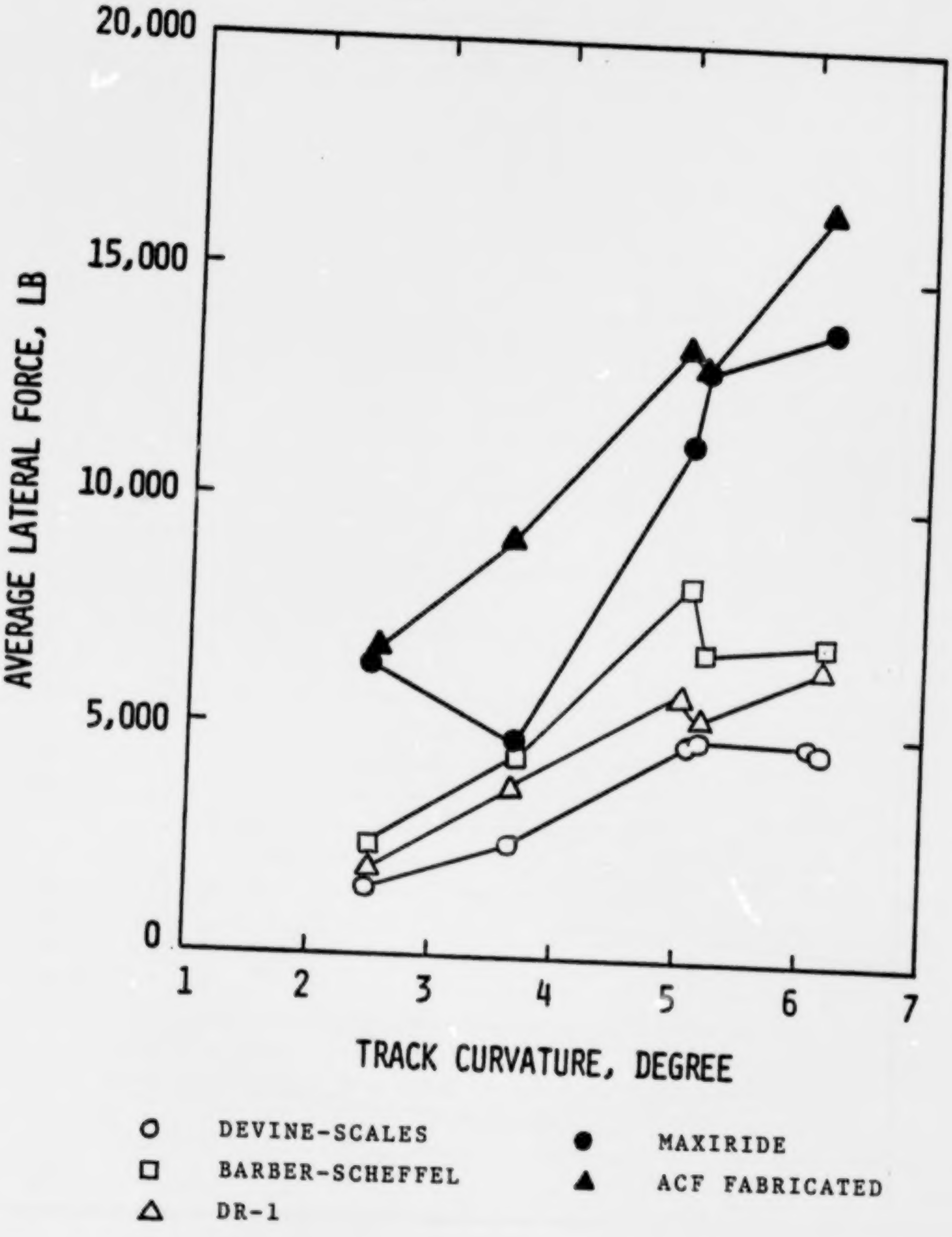

FIG. 4.7 COMPARISON OF LATERAL FORCE VERSUS CURVATURE: ALL TRUCKS, LOADED CONDITION - EXPERIMENTAL DATA

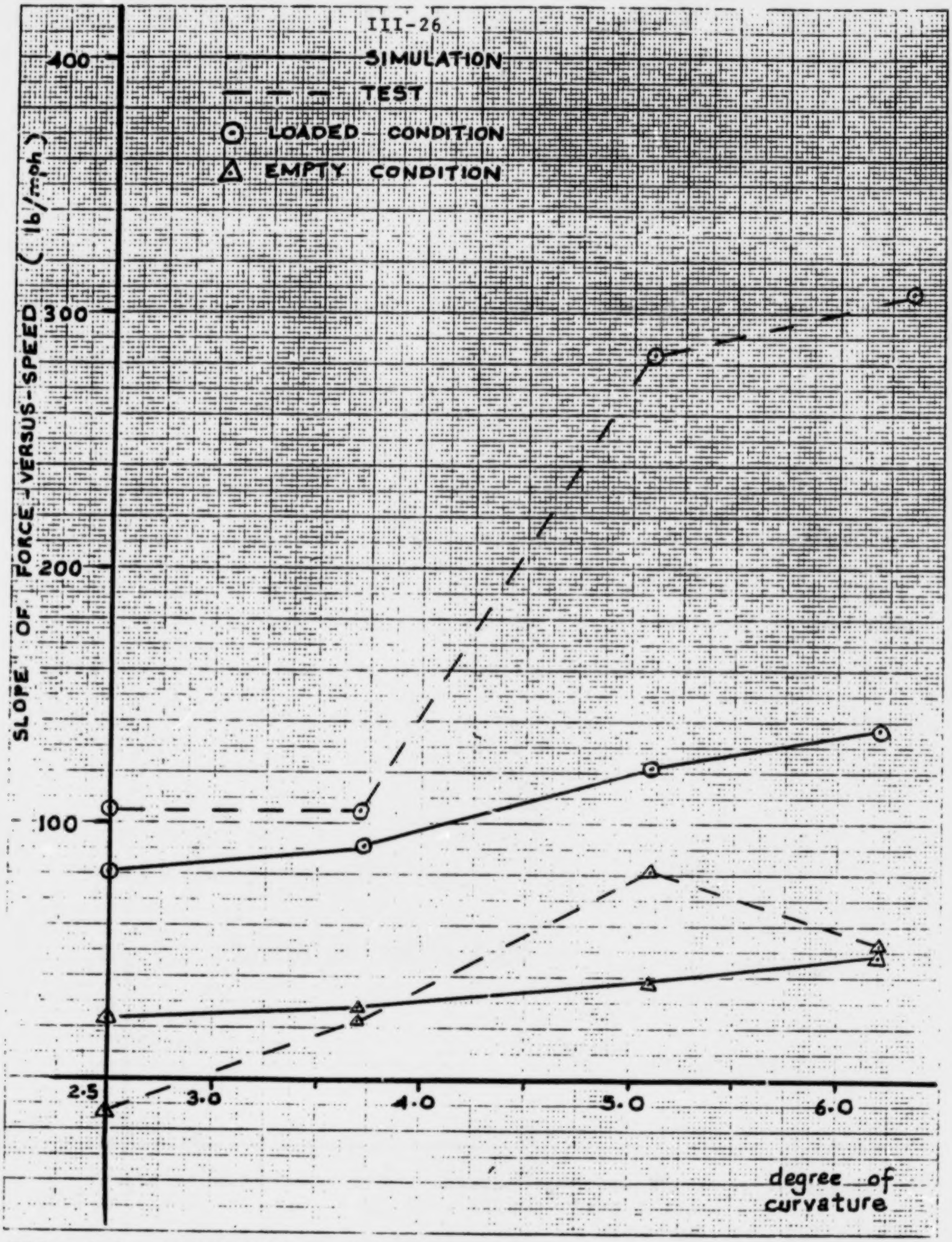

FIG. 4.8 COMPARISON OF SENSITIVITY OF LATERAL FORCE-VERSUS-SPEED AT FOUR CURVATURES: DR-1 TRUCK

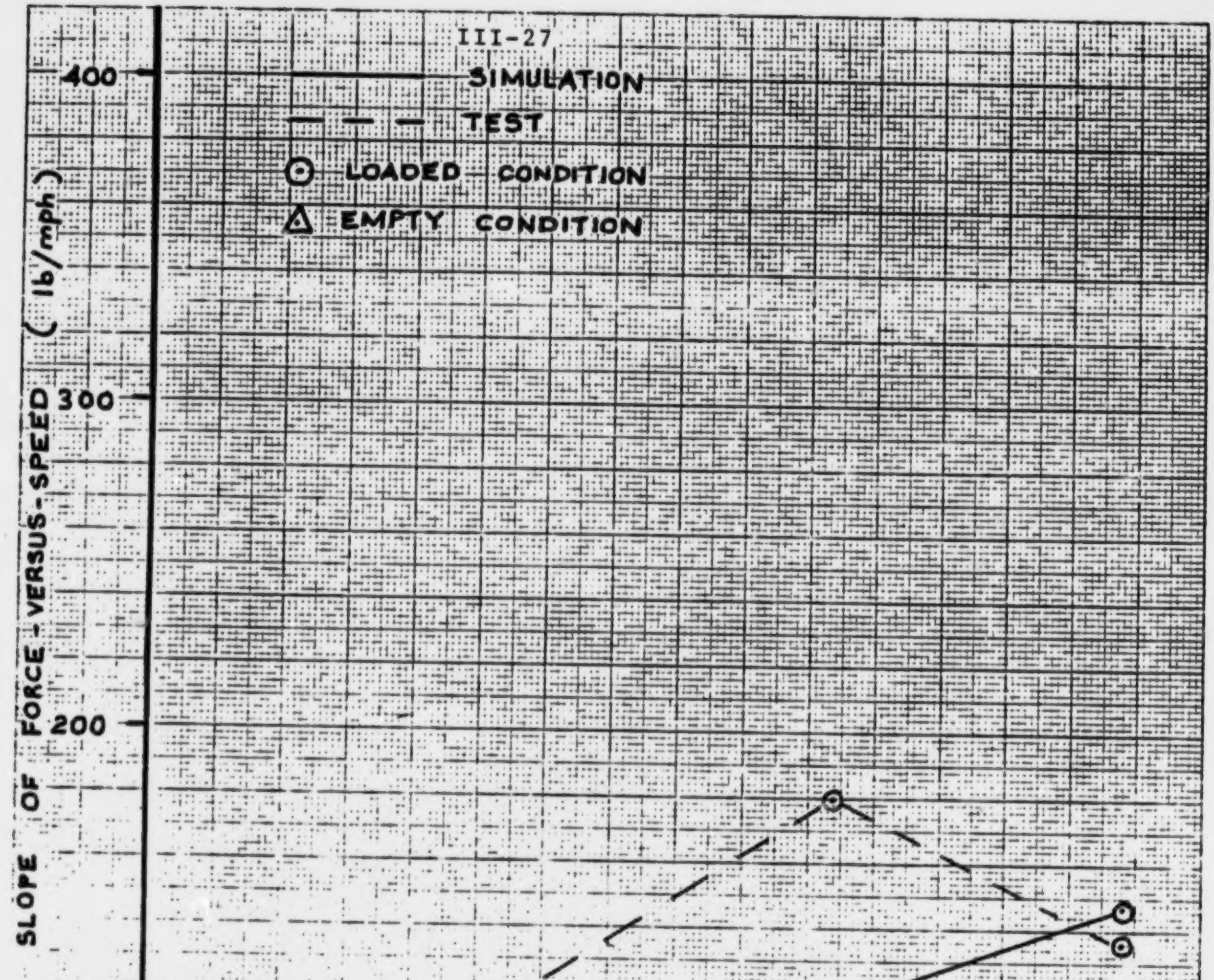

FIG. 4.9 COMPARISON OF SENSITIVITY OF LATERAL FORCE-VERSUS-SPEED AT FOUR CURVATURES: BARBER-SCHEFFEL TRUCK

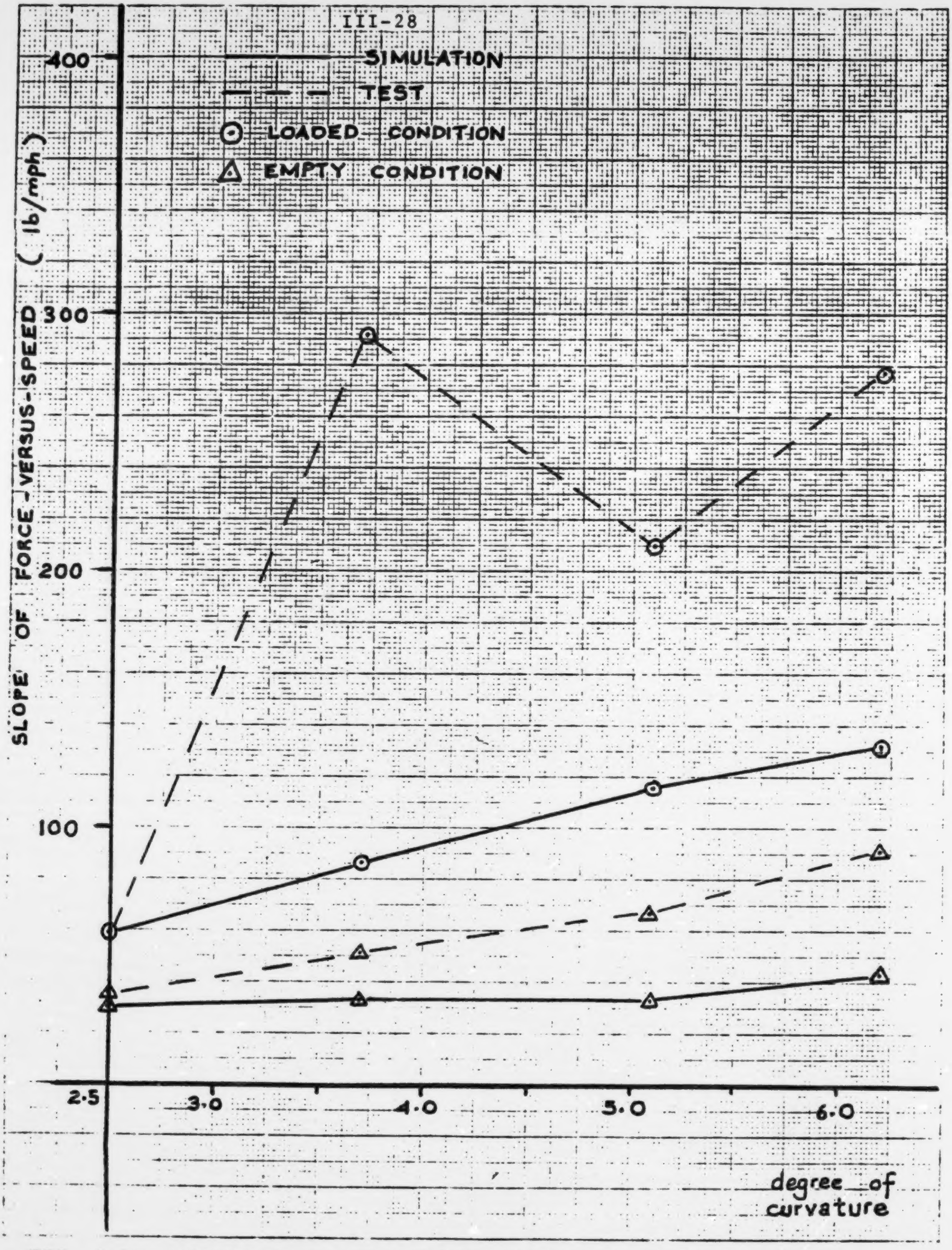

FIG. 4.10 COMPARISON OF SENSITIVITY OF LATERAL FORCE-VERSUS-SPEED AT FOUR CURVATURES: DEVINE-SCALES TRUCK

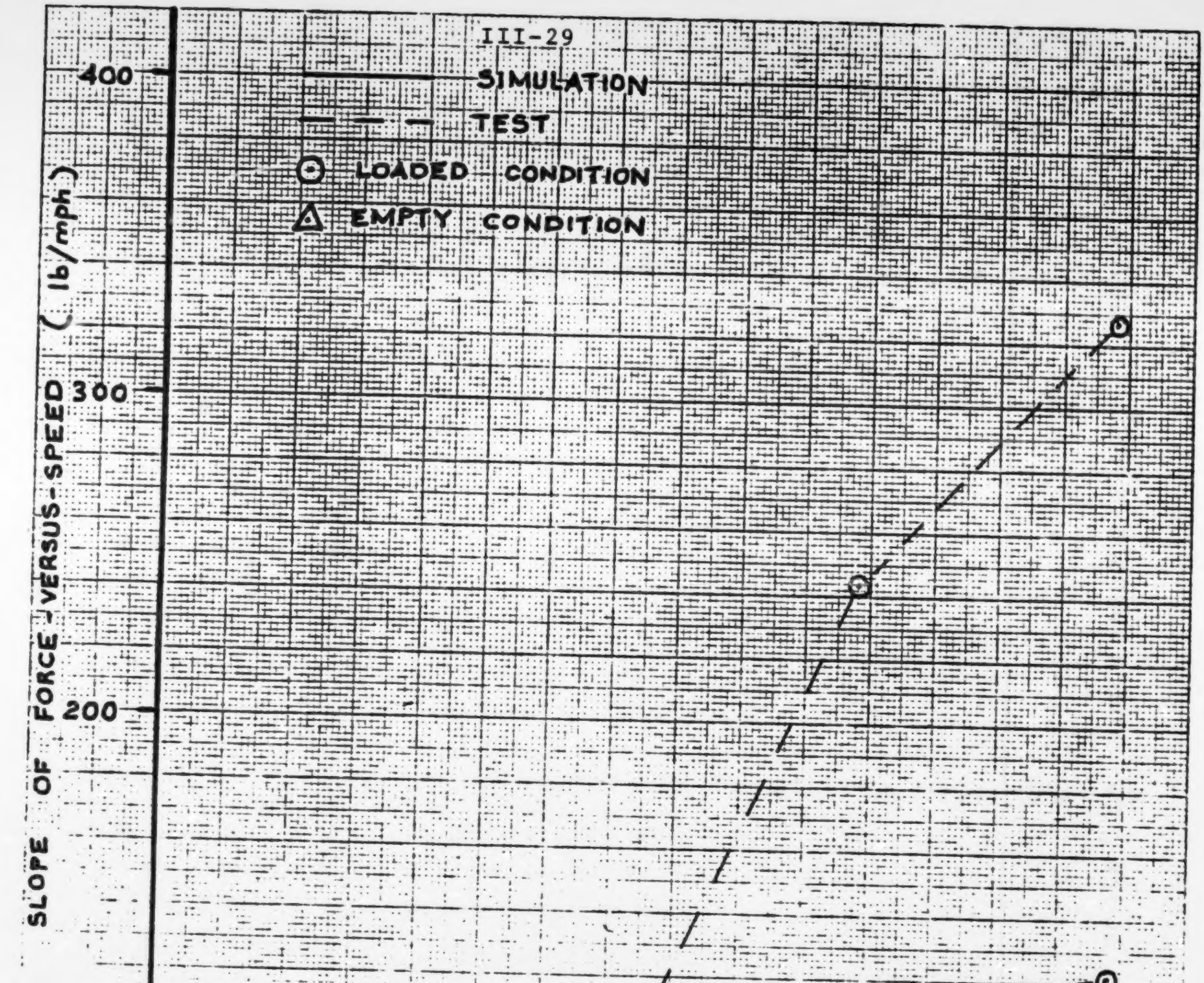

FIG. 4.11 COMPARISON OF SENSITIVITY OF LATERAL FORCE-VERSUS-SPEED AT FOUR CURVATURES: MAXIRIDE TRUCK

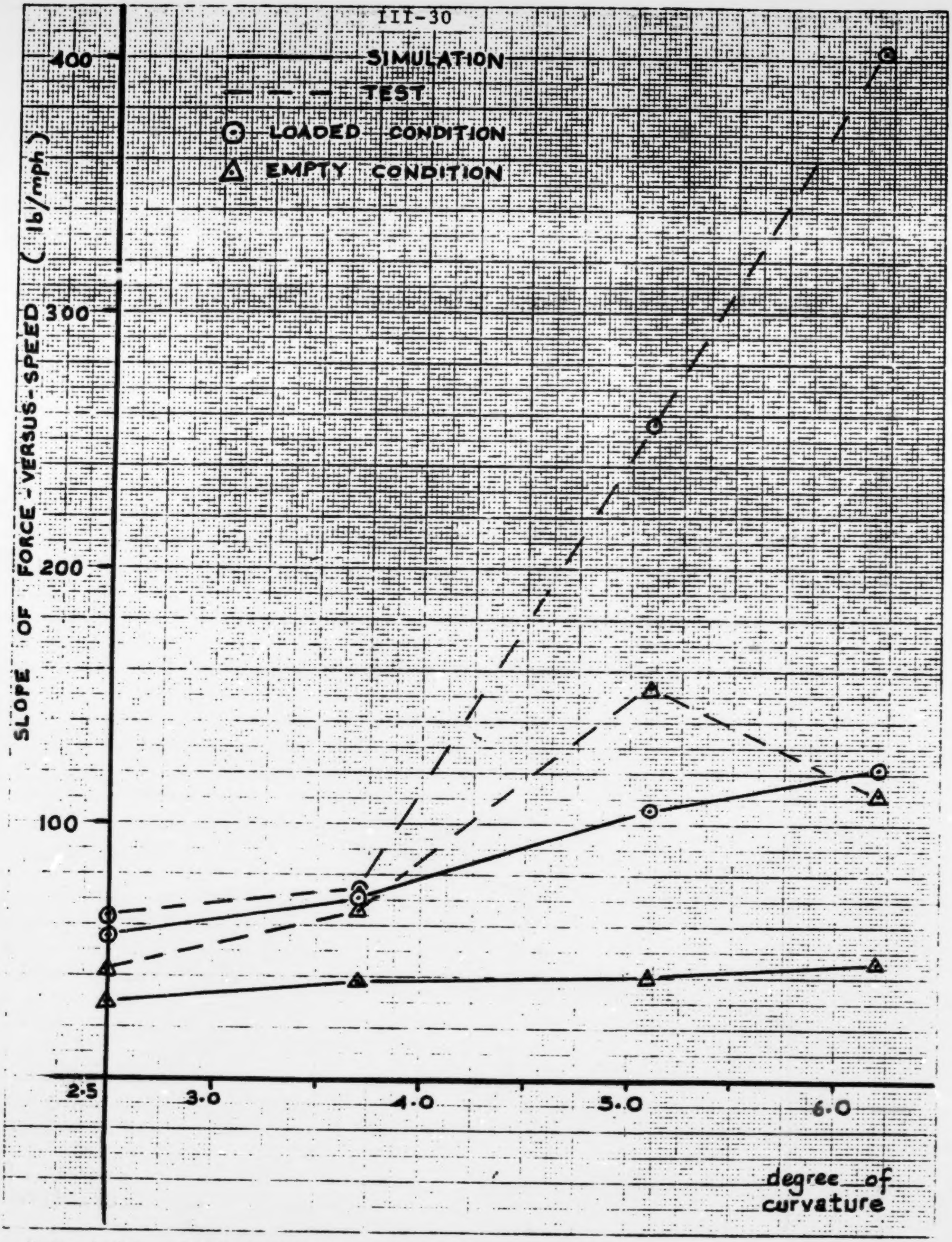

FIG. 4.12 COMPARISON OF SENSITIVITY OF LATERAL FORCE-VERSUS-SPEED AT FOUR CURVATURES: SWING MOTION TRUCK

5.0 PARAMETER SENSITIVITY ANALYSIS FOR TYPE II TRUCKS

The sensitivity of the curving performance of the six Type II trucks was determined for a selected number of input parameters for each truck. The parameters which were chosen to be studied related to:

i) stiffnesses of the trucks
ii) travels and clearances of the trucks
iii) the co-efficient of friction between the wheel and rail

Also, for the Scales truck, the effect of having a modified steering link geometry tending to oversteer or understeer the wheelsets was also studied.

As was done for the Type I truck curving analysis, only one of the selected parameters was varied at a time. The remaining parameters were the same as for the baseline truck and vehicle (i.e. loaded 100 ton car with wheelsets having modified CN Heumann profiles). The simulations were performed for each of the four degrees of track curvature, but at the balance speed only.

Graphs of the lateral force and angle of attack of each wheelset versus the varied parameter were made for the simulation runs on the 6.2° curve. (Figures 5.1 to 5.20). It is important to note that the trends described below were drawn from examinations of the results on the 6.2 degree curve only. It is possible the trends may be different for other degrees of track curvature, superelevation deficiencies, or wheel profiles.

5.1 PARAMETER SENSITIVITY: DR-1 TRUCK

Two parameters were selected for the sensitivity analysis for the DR-1 truck: the inter-axle lateral stiffness and the longitudinal stiffness due to the rubber pads at the axle bearings. The values of the inter-axle stiffness were:

18,000 lb/in.
36,000 lb/in. (baseline)
72,000 lb/in.

Fig. 5.1 shows that for this range of stiffness, there is not much effect on the forces or angles of attack. The results indicate, however, that increasing the inter-axle stiffness allows the lead wheelset to become more radial. Decreasing it allows the trailing wheelset to flange (as indicated by computer output not included in the report) and reduces the inward lateral force on the outer wheel.

Three values of longitudinal stiffness were examined:

7,500 lb/in.
15,000 lb/in. (baseline)
30,000 lb/in.

Fig. 5.2 shows that increasing this stiffness causes large increases in the lateral force and angle of attack of the leading wheelset. This is because the longitudinal stiffness resists the steering action of the wheelsets to align themselves radially with the curve so as to create larger angles of attack and larger forces.

5.2 PARAMETER SENSITIVITY: BARBER-SCHEFFEL TRUCK

As for the case of the DR-1 truck, the inter-axle lateral stiffness and longitudinal pad stiffness were selected for the parameter sensitivity of the Barber-Scheffel truck. The values of the inter-axle stiffness were:

4,500 lb/in.
9,000 lb/in. (baseline)
18,000 lb/in.

The effect of varying the inter-axle stiffness for the Barber-Scheffel truck is shown in figure 5.3. It can be seen that increasing the inter-axle stiffness causes a decrease in the angle of attack of the leading wheelset and in the lateral force acting on the outer wheel of the trailing wheelset.

The parameter values of the longitudinal stiffness were selected to be:

3,750 lb/in.
7,500 lb/in. (baseline)
15,000 lb/in.

As seen in figure 5.4, increasing the longitudinal stiffness makes the truck more "square", which causes an increase in the lateral force and angle of attack of the leading wheelset, while decreasing those for the trailing wheelset.

5.3 PARAMETER SENSITIVITY: DEVINE-SCALES TRUCK

For the Devine-Scales truck, three parameters were varied:

the lateral pedestal stiffness between the wheelsets and frame, the stiffness of the body link in the steering mechanism, and the position of the steering axle point on the steering link (distance "C" in figure 3.1).

For the lateral pedestal stiffness, the following values were used:

50,000 lb/in.
100,000 lb/in.
200,000 lb/in. (baseline)

Figure 5.5 shows the major influence of the lateral pedestal stiffness is on the lateral force acting on the outer wheel of the trailing wheelset. By decreasing the lateral stiffness, the magnitude of the lateral force initially decreases, crosses zero and then begins to increase. Decreasing the lateral stiffness also reduces the force on the outer wheel of the leading wheelset, though this effect is much smaller.

The body link stiffness was varied from 25,000 lb/in. to 200,000 lb/in. As seen in figure 5.6, the curving performance of the truck is not sensitive to this range of stiffnesses.

Three values of the position of the axle steering point were selected:

1.50" ... understeered
1.747" ... ideal steering (baseline)
2.00" ... oversteered

Figure 5.7 shows this parameter has a large influence on the truck's curving performance, particularly for the leading wheelset.

The 2.00" link position causes the leading wheelset to have a negative angle of attack (that is, rolling towards the low rail) and decreases its lateral force. The 1.50" link position increases both the angle of attack and lateral force of the leading wheelset.

5.4 PARAMETER SENSITIVITY: MAXIRIDE TRUCK

Two parameters were varied for the Maxiride truck: the lateral and longitudinal clearances, three values were examined:

: 1/64"
: 1/32" (baseline)
: 1/16"

Figure 5.8 shows that by having some amount of longitudinal pedestal clearance, the truck uses this clearance to align the leading wheelset in a more radial position. As seen in the figure, the larger the clearance, the lower is the lateral force and angle of attack on the leading wheelset. For the range of clearances examined, there is no significant change to the curving of the trailing wheelset.

The values of the lateral clearance were selected to be ¼", ½" and ¾". From figure 5.9, it is seen that for these values of clearances, there is no change to the curving behaviour of the truck.

5.5 PARAMETER SENSITIVITY: SWING MOTION TRUCK

For the Swing Motion truck, three parameters were varied:

the wheelbase, the parallelogramming stiffness, and the lateral clearance between the axle and the bearing. The wheelbase was varied from 70 to 75 inches, the parallelogramming stiffness from 100,000 to 500,000 lb/in. and the axle clearance from zero to 1/8 inch. Figures 5.10, 5.11 and 5.12 show that within these ranges, there are only small effects from these parameters on the truck's performance. The most significant of these effects are: (i) a small increase in the leading wheelset's angle of attack with an increase in wheelbase, and (ii) a slight reduction in the lateral force of the leading wheelset with an increase in axle clearance.

5.6 PARAMETER SENSITIVITY: ACF TRUCK

The parameters selected to be varied for the ACF truck were the parallelogramming stiffness and the longitudinal stiffness of the bearing rings. The values of the parallelogramming stiffness were selected to be:

15,000 lb/in.
30,000 lb/in. (baseline)
60,000 lb/in.

The effects of this stiffness on the lateral force and angle of attack is shown in figure 5.13. Like the Swing Motion truck, this parameter is found to have little effect on the curving of the truck.

The longitudinal stiffness of the truck was varied from 100,000 to 500,000 lb/in. Figure 5.14 shows that by reducing the stiffness, the leading wheelset is allowed to steer so that there is a decrease in its angle of attack and lateral force.

For this range of longitudinal stiffness, however, there is no effect on the trailing wheelset.

5.7 PARAMETER SENSITIVITY: COEFFICIENT OF FRICTION

The sensitivity of the curving performance to the coefficient of friction was studied for each of the Type II trucks. Three values of the coefficient were selected: 0.3, 0.4, and 0.5. The effects of varying this parameter are shown in figures 5.15 to 5.20.

For the three steering type trucks (i.e. DR-1, Scheffel, and Scales), the major influence of increasing the coefficient of friction is to reduce the lateral force of the outer leading wheel. This is because the higher values of friction allow larger steering forces to be generated at the points of contact between the wheel and rail. Note that for the Scales truck, the influence of friction is less because the wheelsets have already been forced to steer by its linkage mechanism. There is little influence on the trailing wheelset due to changes in the coefficient of friction for these three trucks.

For the non-steering type trucks (i.e. Maxiride, Swing Motion and ACF), increasing the coefficient of friction reduces the lateral force on the outer wheel of the leading wheelset and increases the force on the trailing wheelset. Also, it can be seen that the larger coefficient of friction permits the truck as a whole to be more radially aligned with the curve, as demonstrated by the decrease in the angle of attack for the leading wheelset, and the comparable increase for the trailing wheelset.

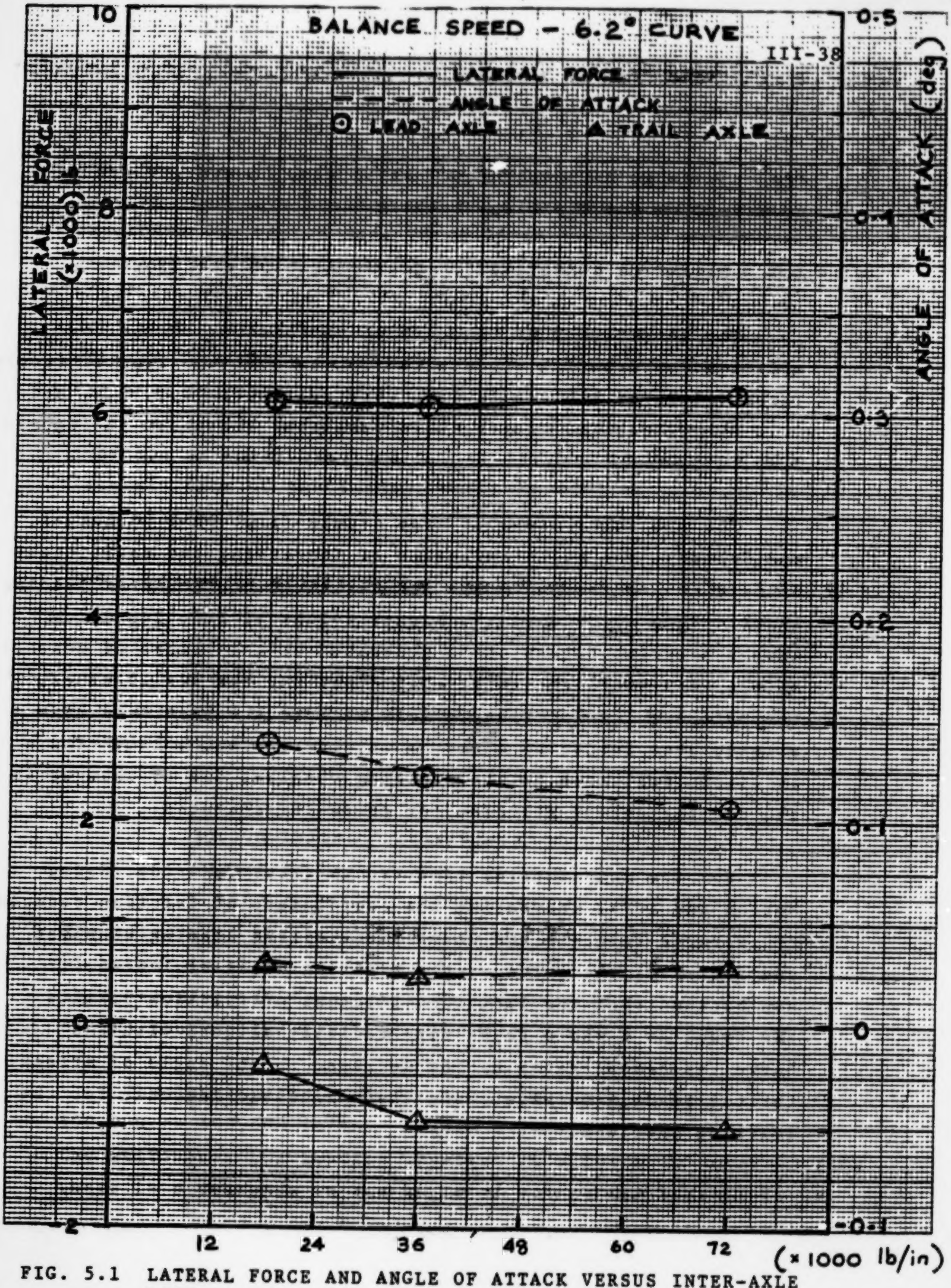

FIG. 5.1 LATERAL FORCE AND ANGLE OF ATTACK VERSUS INTER-AXLE LATERAL STIFFNESS: DR-1 TRUCK

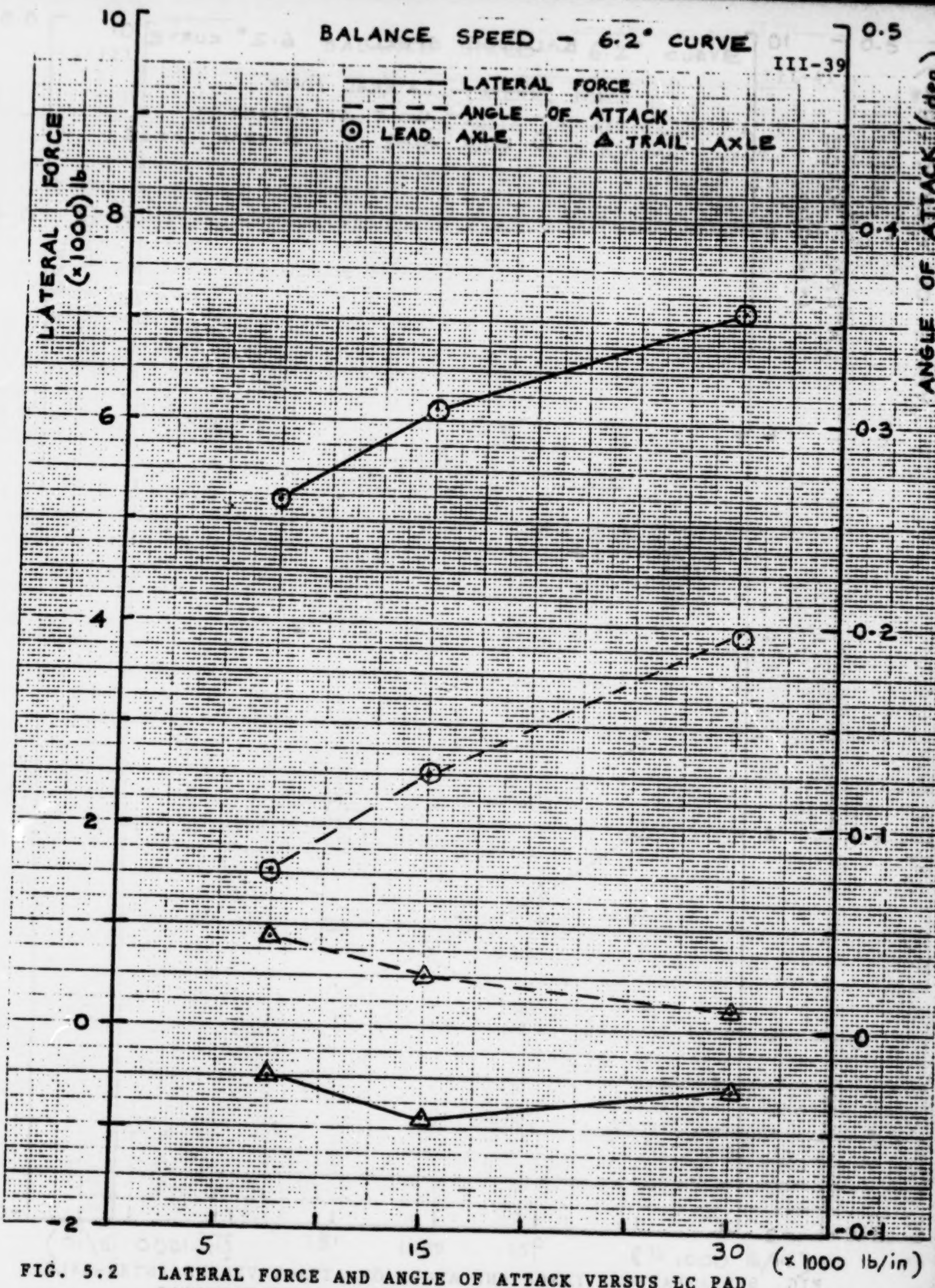

FIG. 5.2 LATERAL FORCE AND ANGLE OF ATTACK VERSUS LC PAD LONGITUDINAL STIFFNESS: DR-1 TRUCK

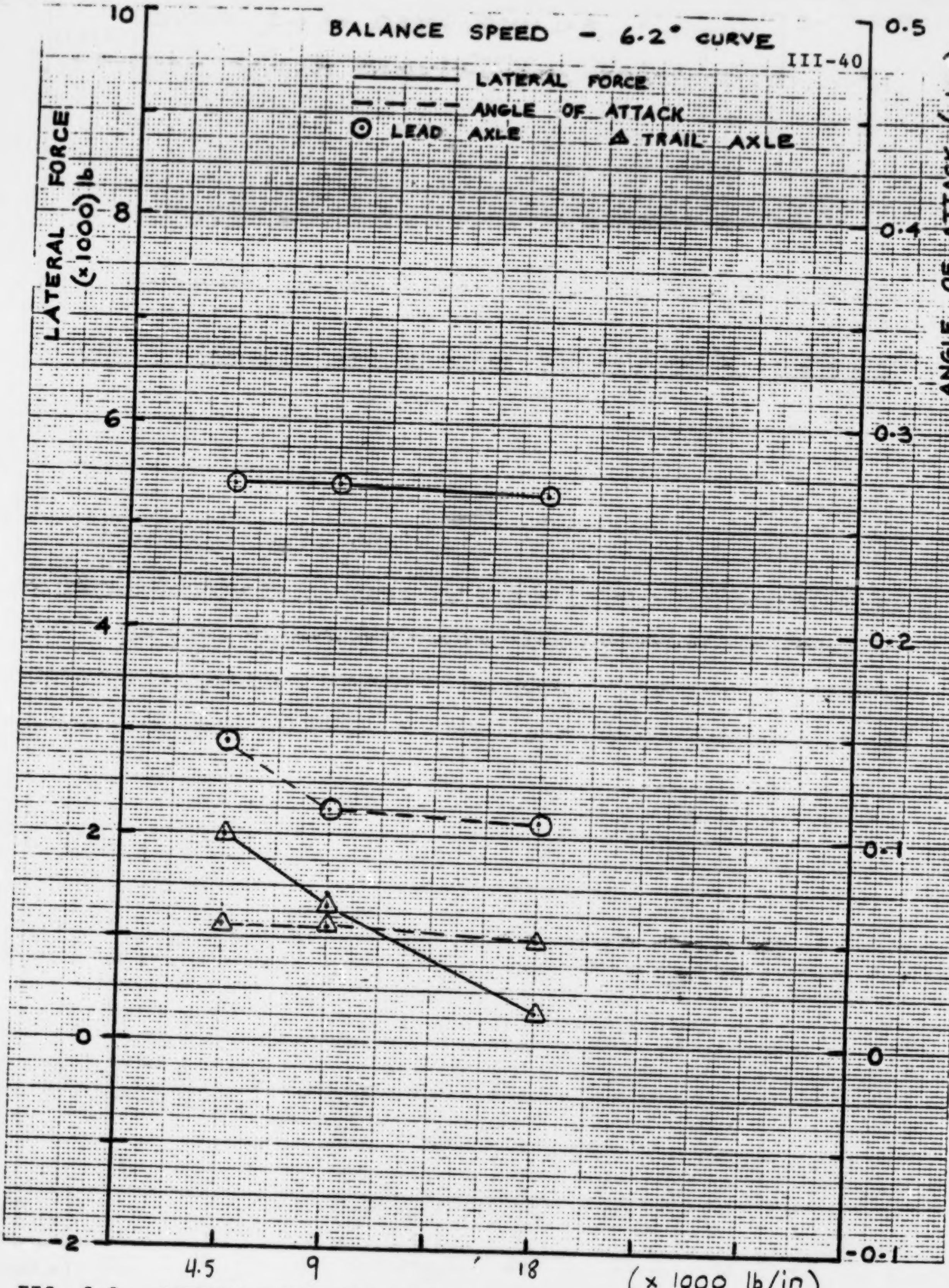

FIG. 5.3 LATERAL FORCE AND ANGLE OF ATTACK VERSUS INTER-AXLE LATERAL STIFFNESS: BARBER-SCHEFFEL TRUCK

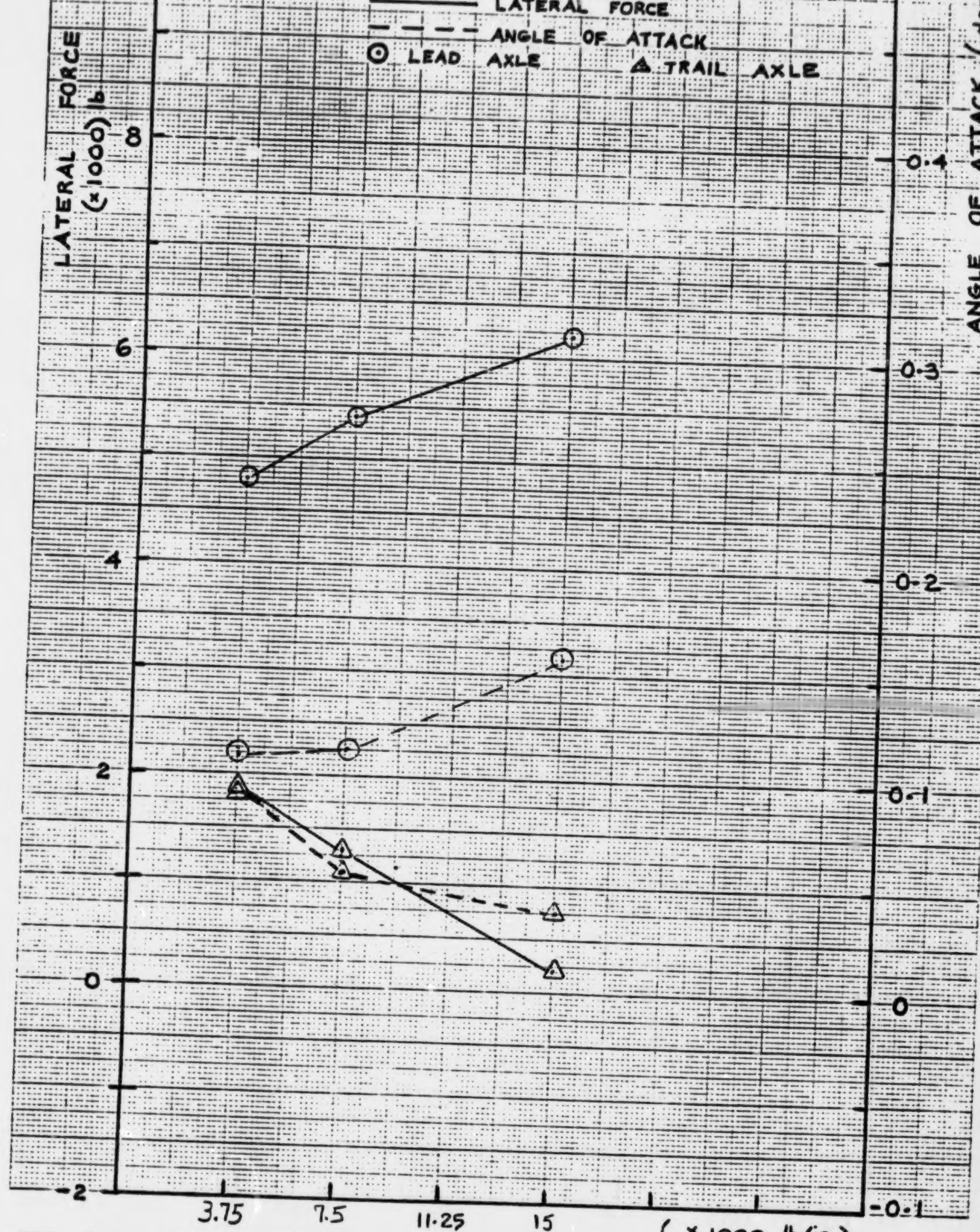

FIG. 5.4 LATERAL FORCE AND ANGLE OF ATTACK VERSUS BEARING PAD LONGITUDINAL STIFFNESS: BARBER-SCHEFFEL TRUCK

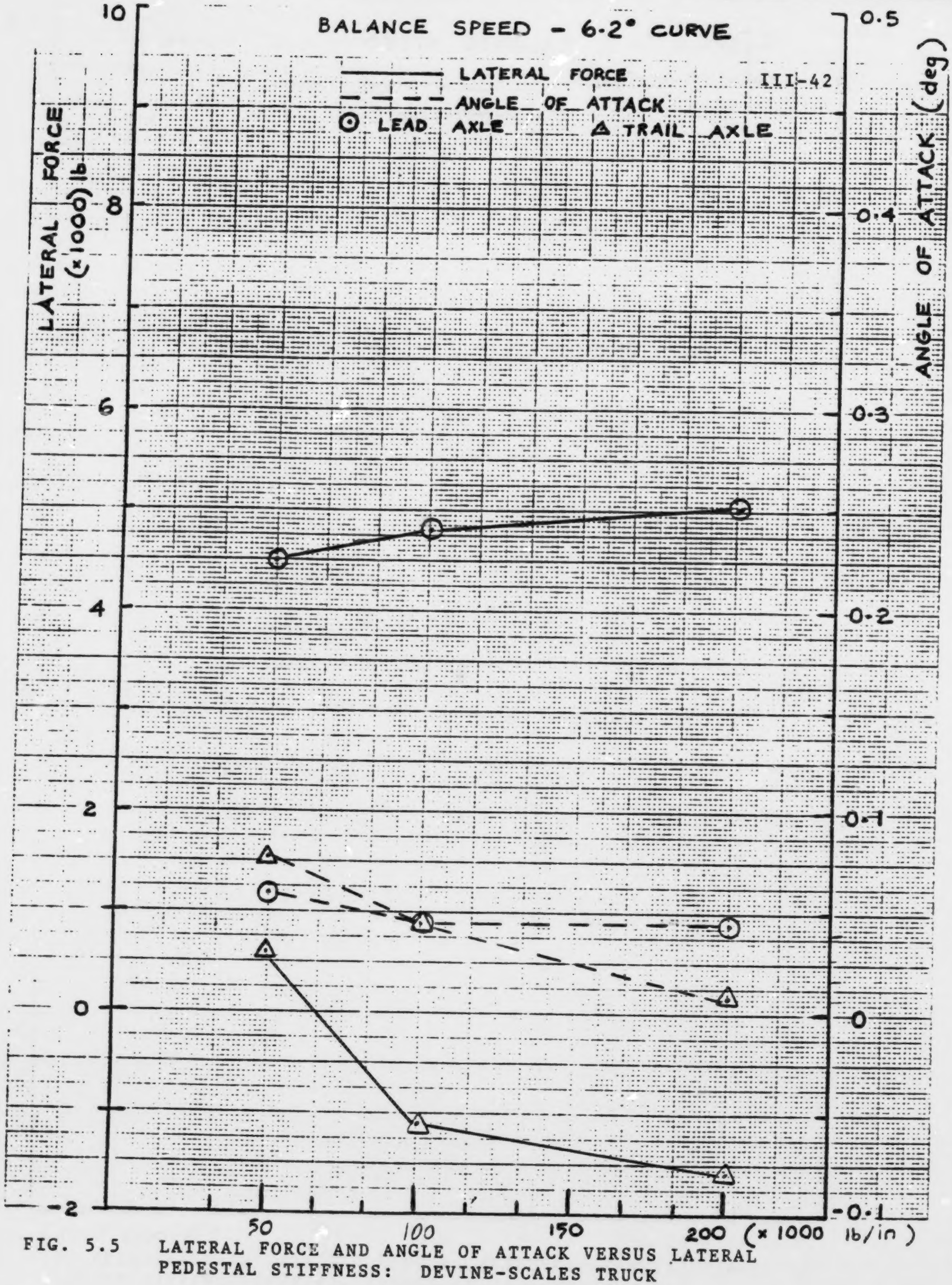

FIG. 5.5 LATERAL FORCE AND ANGLE OF ATTACK VERSUS LATERAL PEDESTAL STIFFNESS: DEVINE-SCALES TRUCK

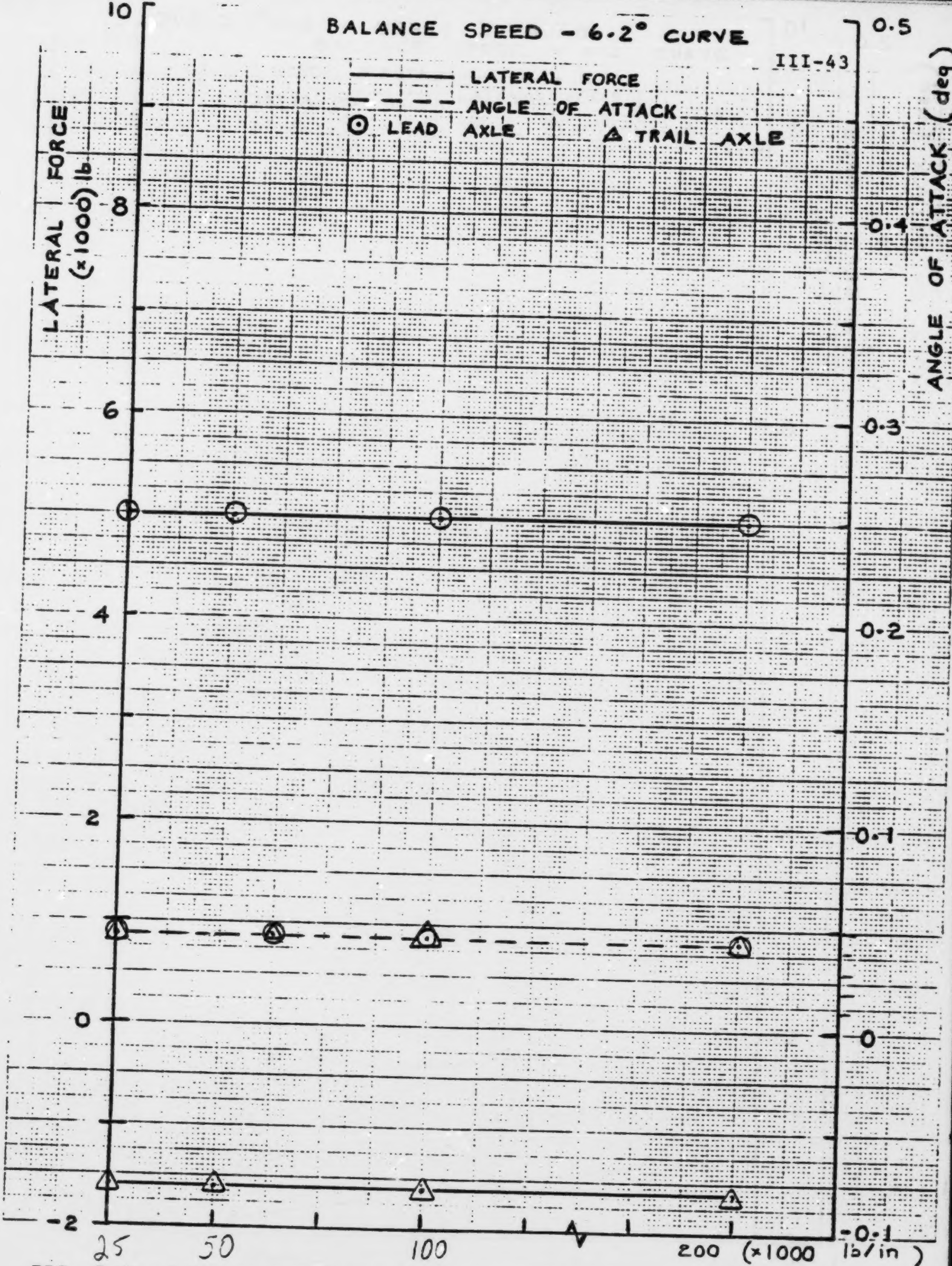

FIG. 5.6 LATERAL FORCE AND ANGLE OF ATTACK VERSUS BODY LINK STIFFNESS: DEVINE-SCALES TRUCK

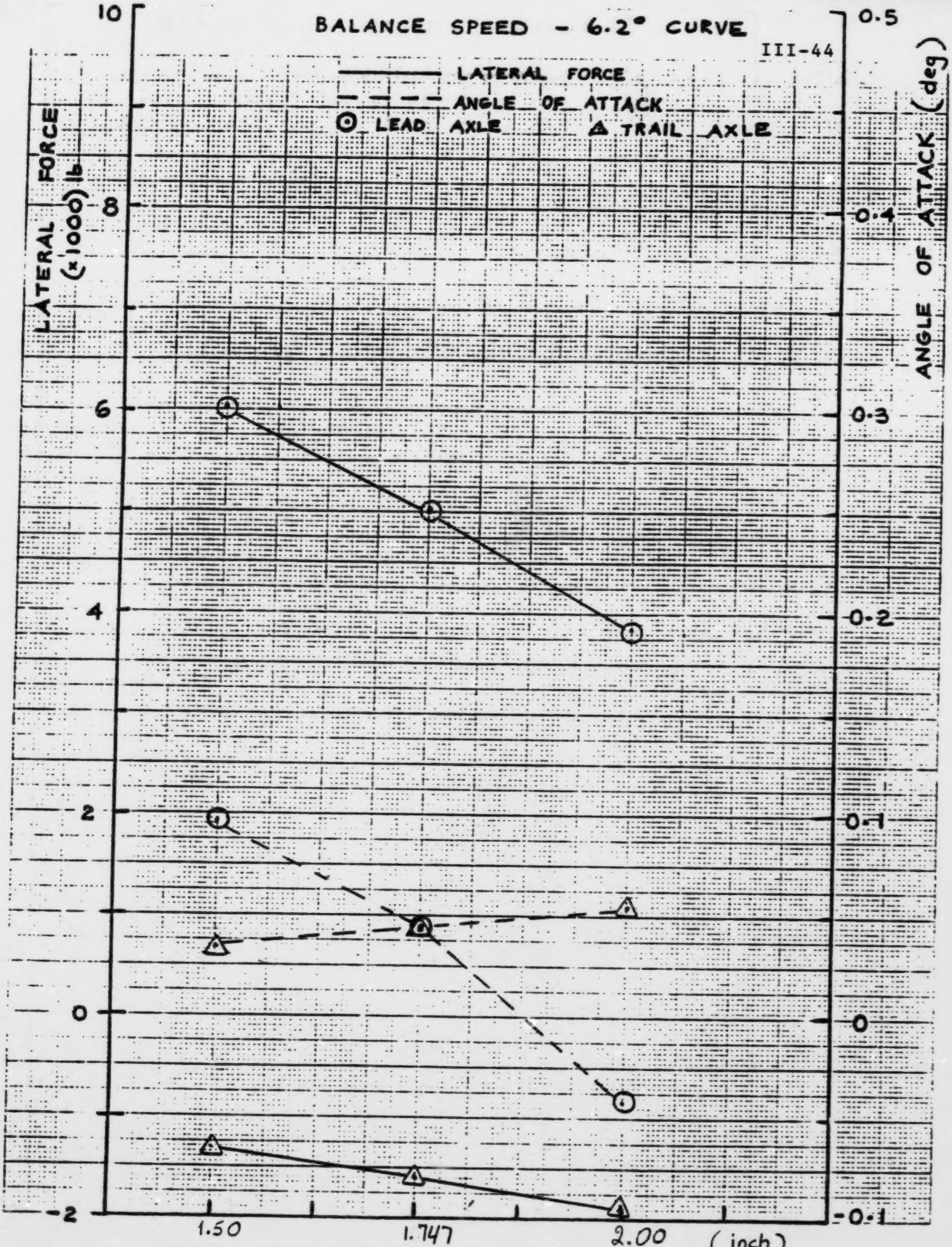

FIG. 5.7 LATERAL FORCE AND ANGLE OF ATTACK VERSUS DISTANCE "C" ON STEERING LINK: DEVINE-SCALES TRUCK

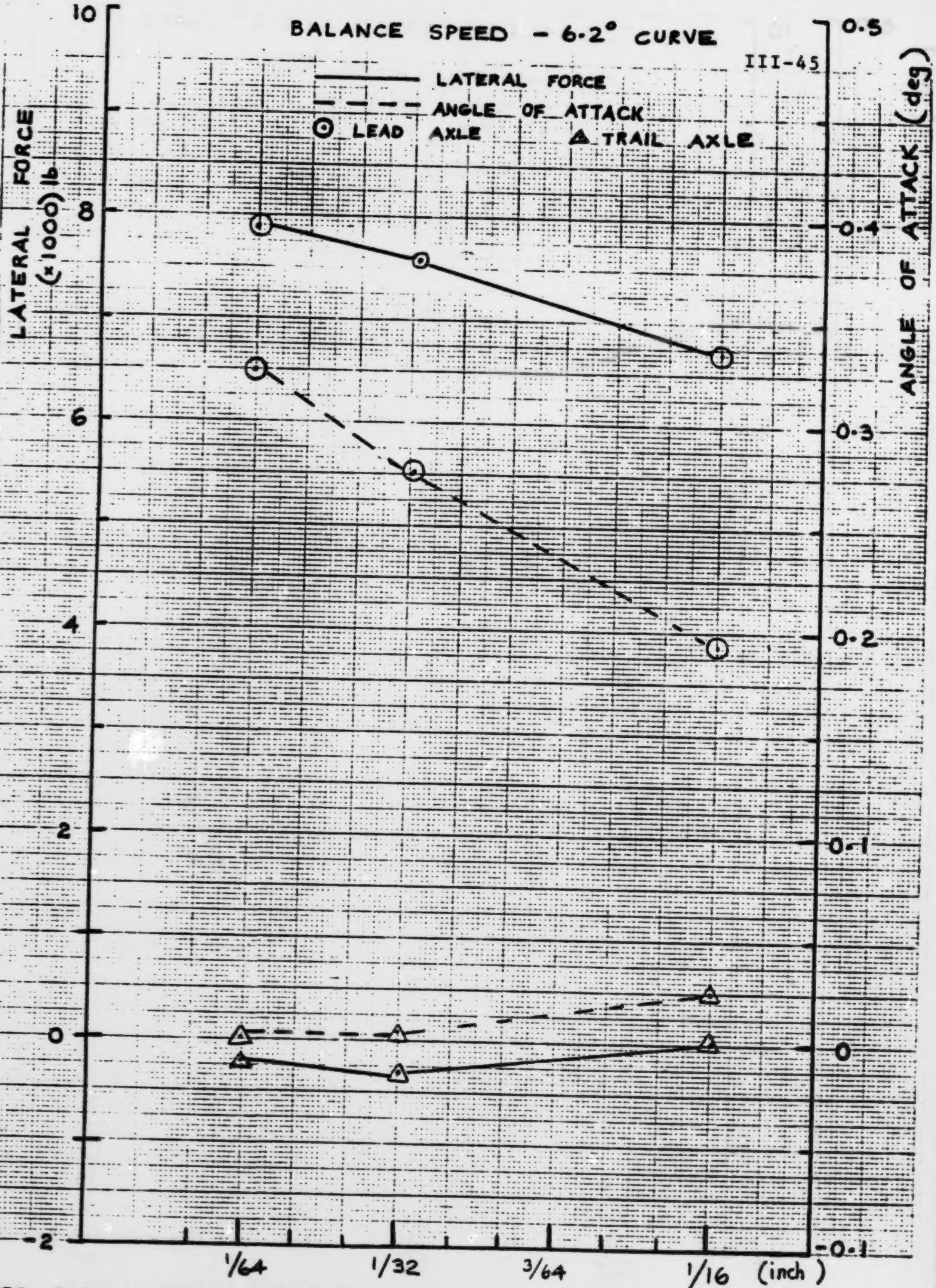

FIG. 5.8 LATERAL FORCE AND ANGLE OF ATTACK VERSUS LONGITUDINAL PEDESTAL CLEARANCE: MAXIRIDE TRUCK

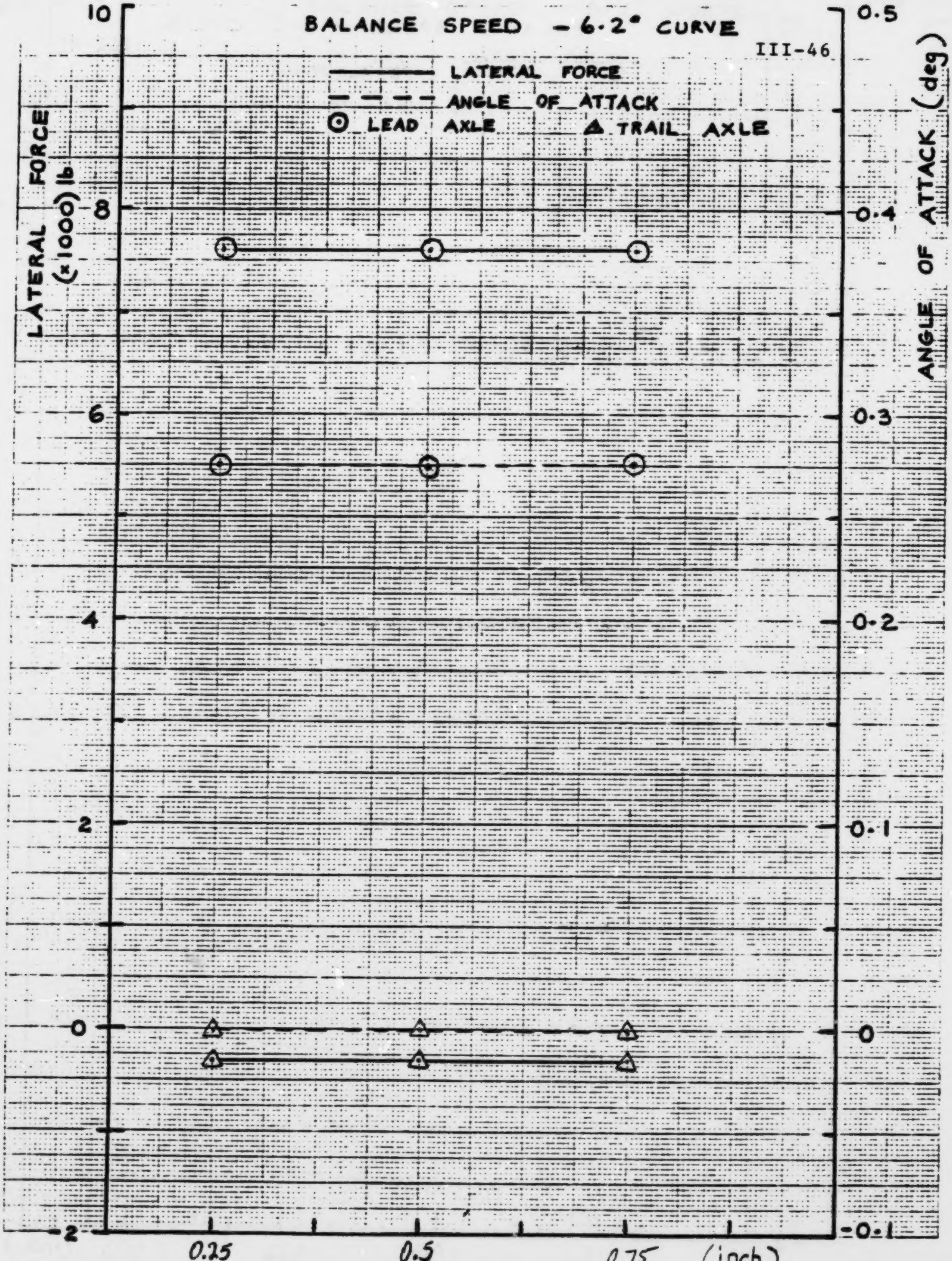

FIG. 5.9 LATERAL FORCE AND ANGLE OF ATTACK VERSUS LATERAL PEDESTAL CLEARANCE: MAXIRIDE TRUCK

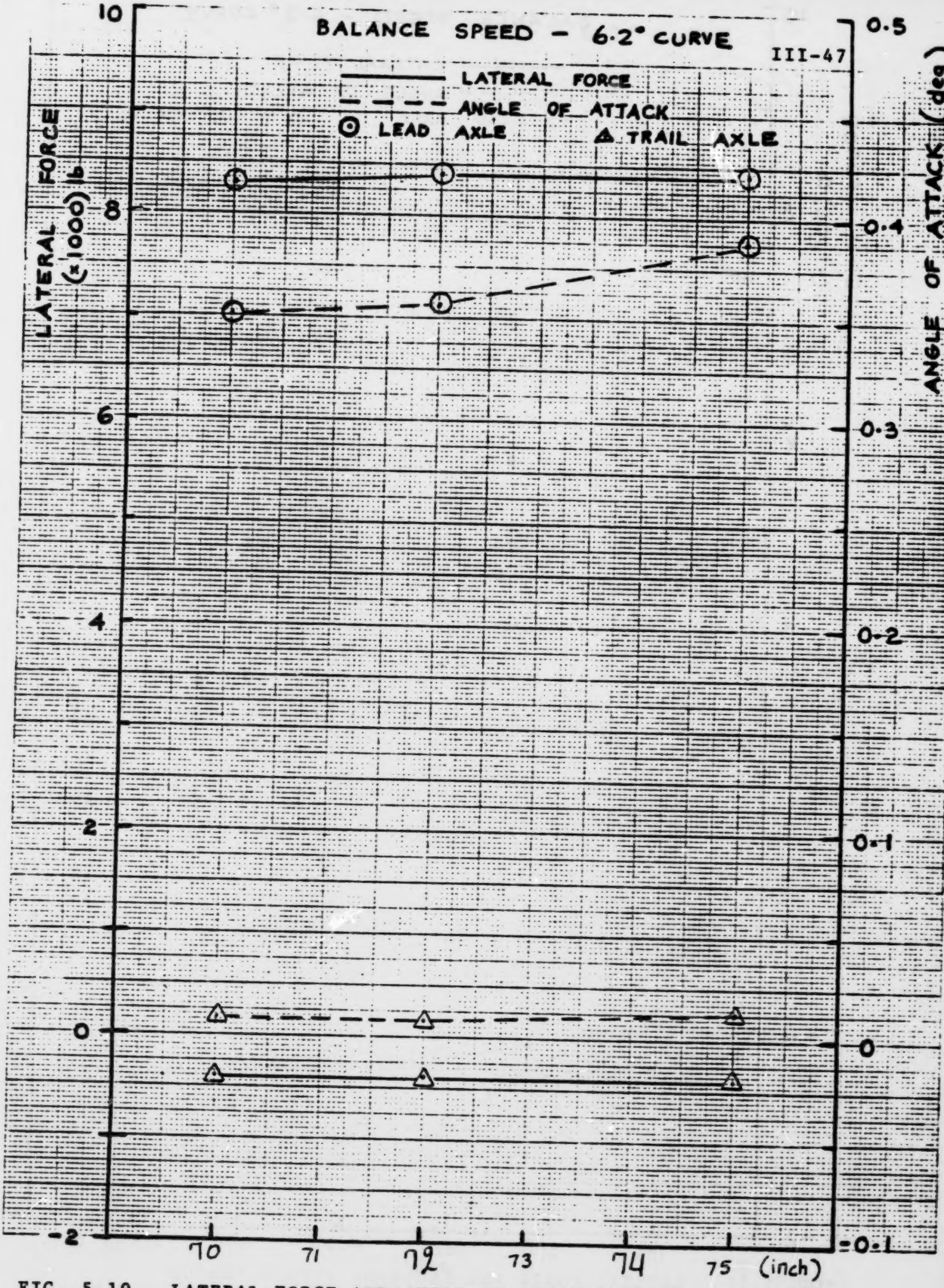

FIG. 5.10 LATERAL FORCE AND ANGLE OF ATTACK VERSUS WHEELBASE : SWING MOTION TRUCK

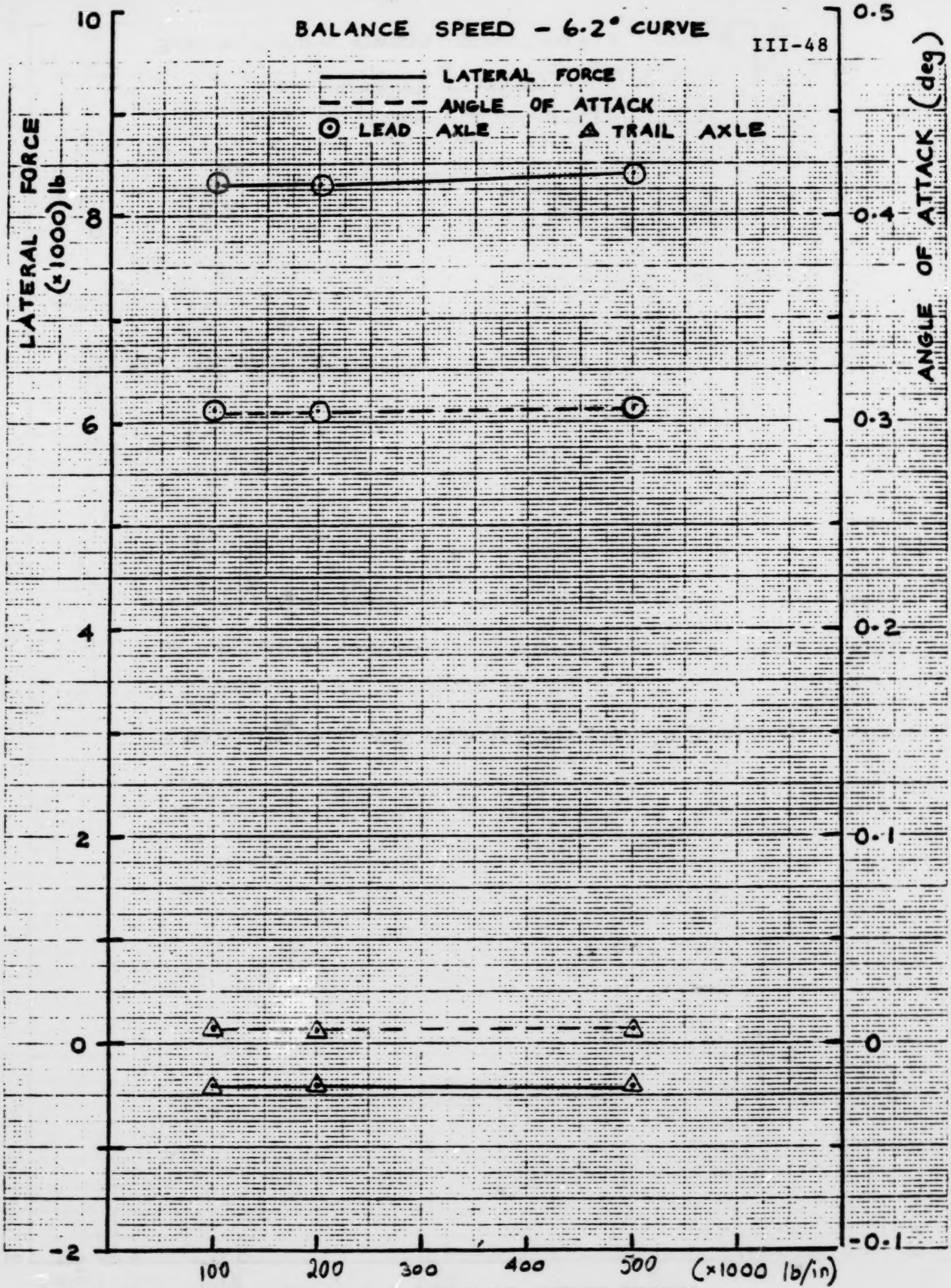

FIG. 5.11 LATERAL FORCE AND ANGLE OF ATTACK VERSUS PARALLELOGRAMMING STIFFNESS: SWING MOTION TRUCK

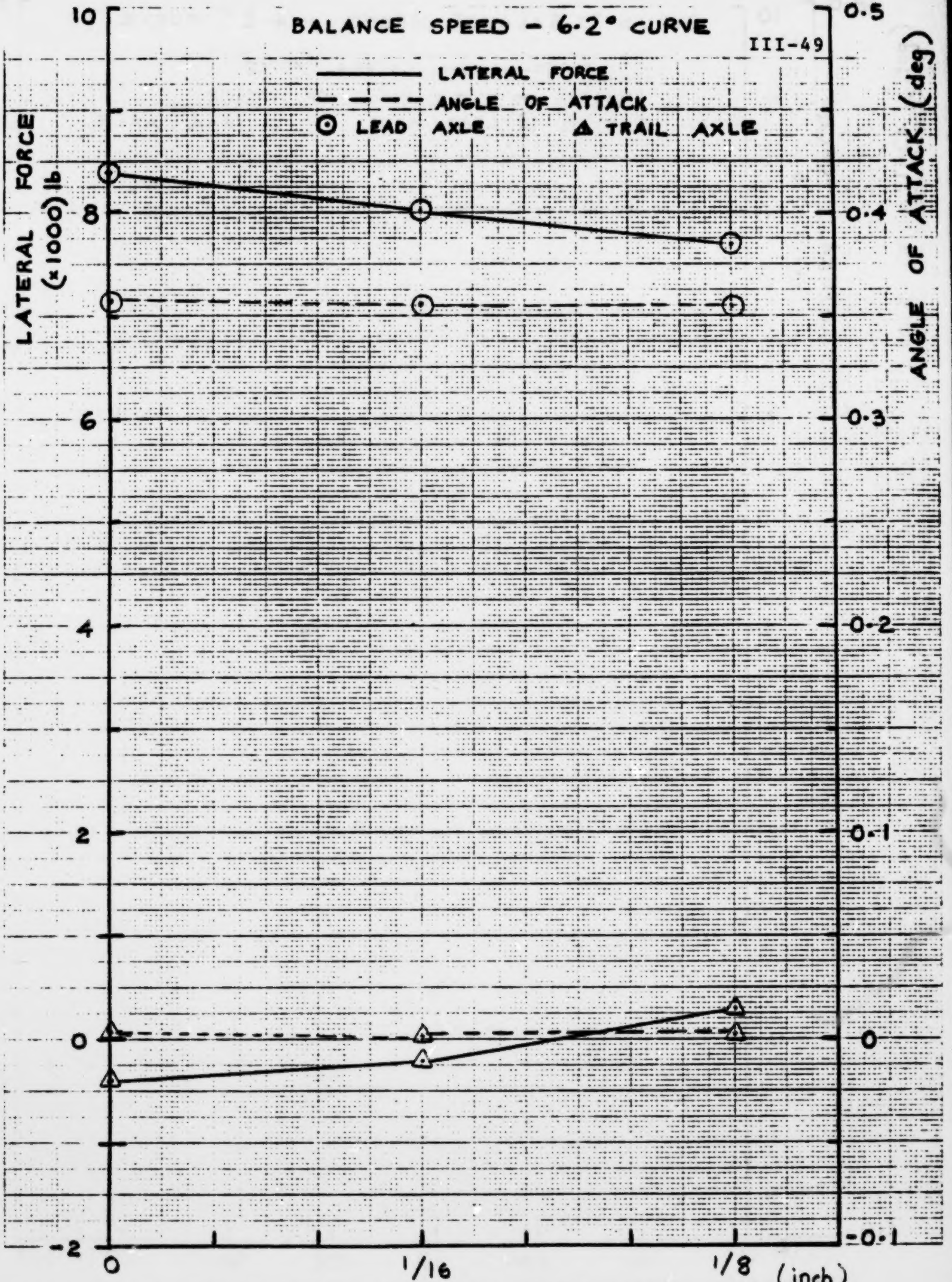

FIG. 5.12 LATERAL FORCE AND ANGLE OF ATTACK VERSUS LATERAL AXLE/BEARING CLEARANCE: SWING MOTION TRUCK

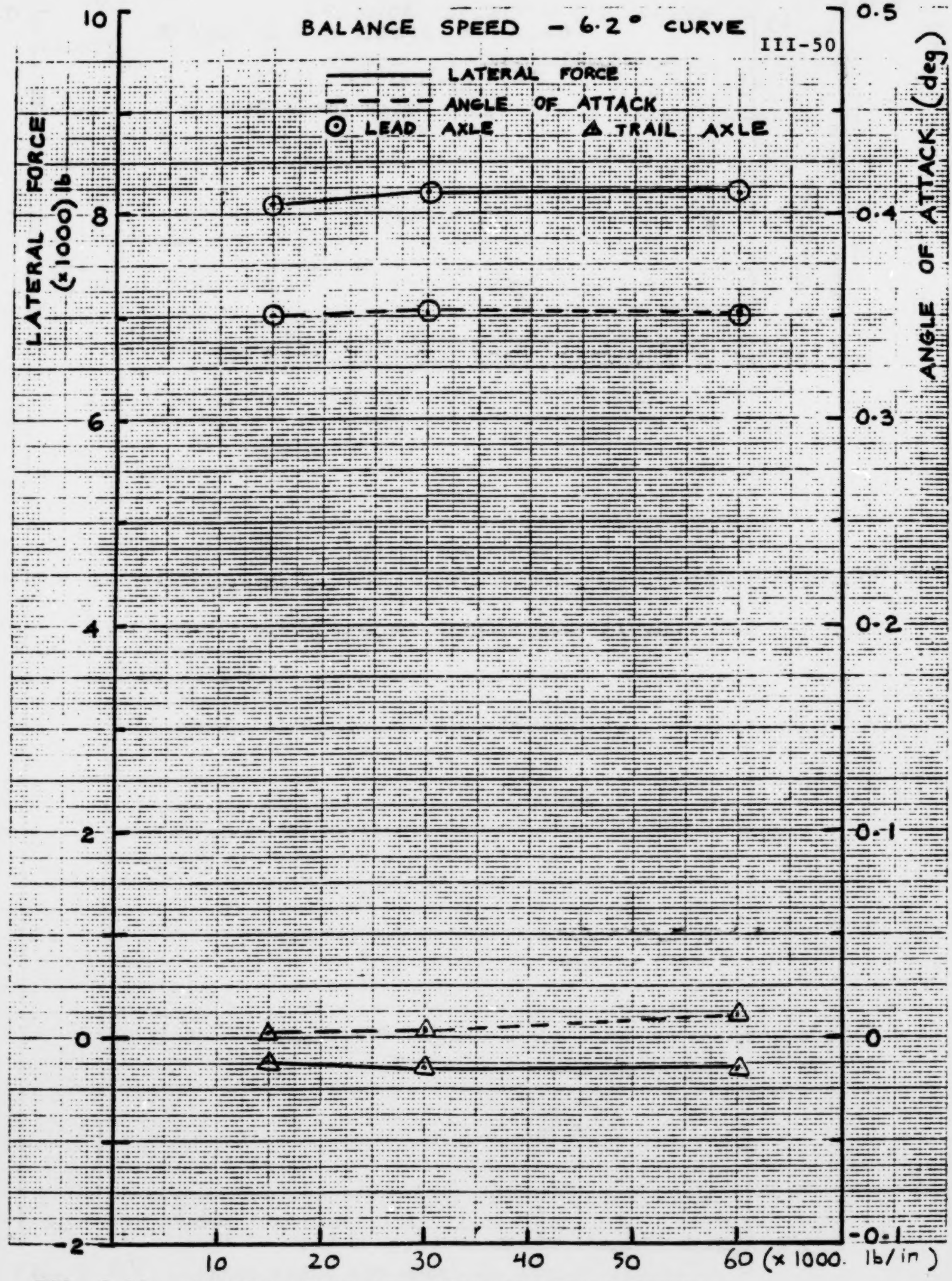

FIG. 5.13 LATERAL FORCE AND ANGLE OF ATTACK VERSUS PARALLELOGRAMMING STIFFNESS: ACF FABRICATED TRUCK

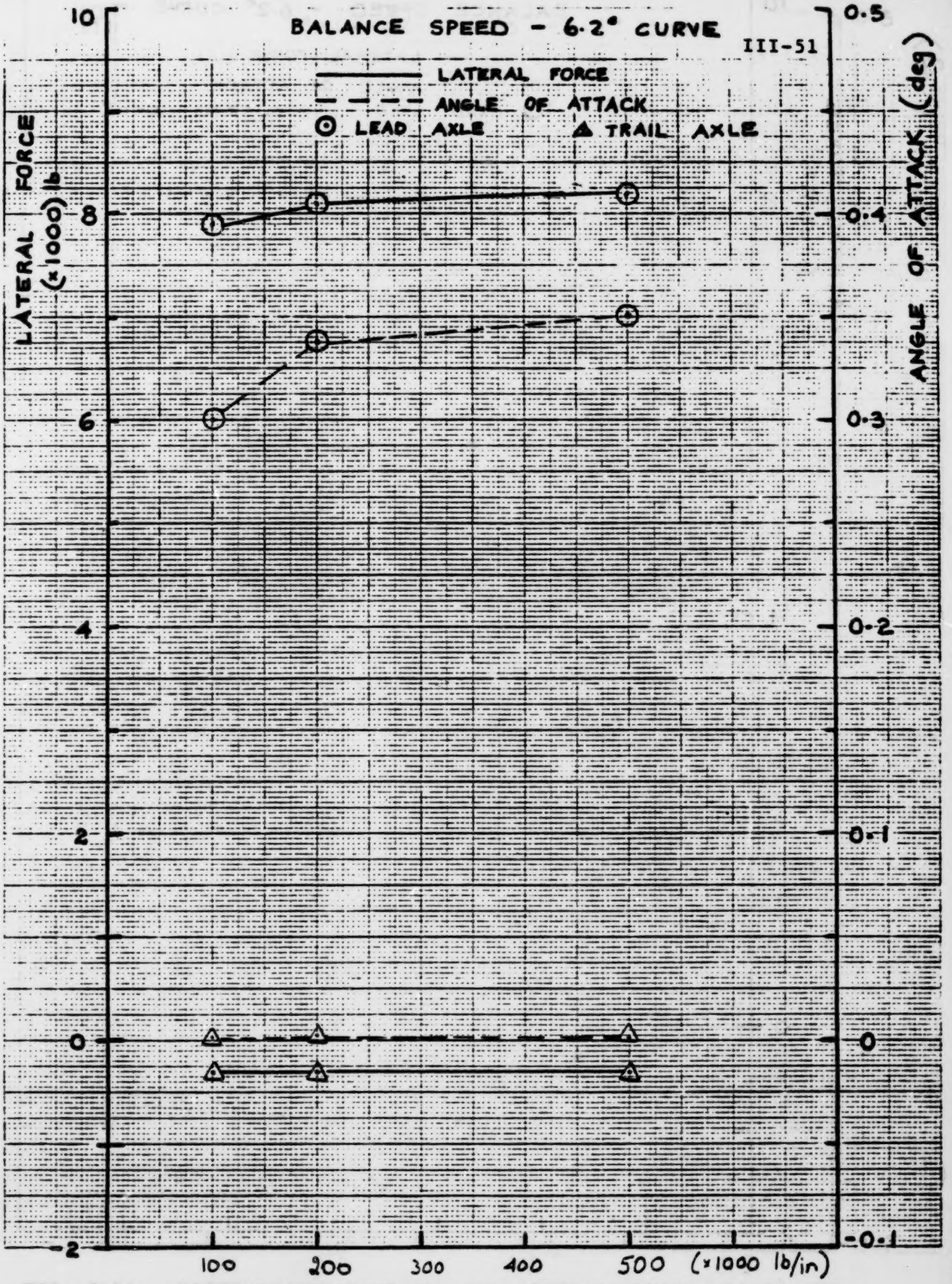

FIG. 5.14 LATERAL FORCE AND ANGLE OF ATTACK VERSUS BEARING RING LONGITUDINAL STIFFNESS: ACF FABRICATED TRUCK

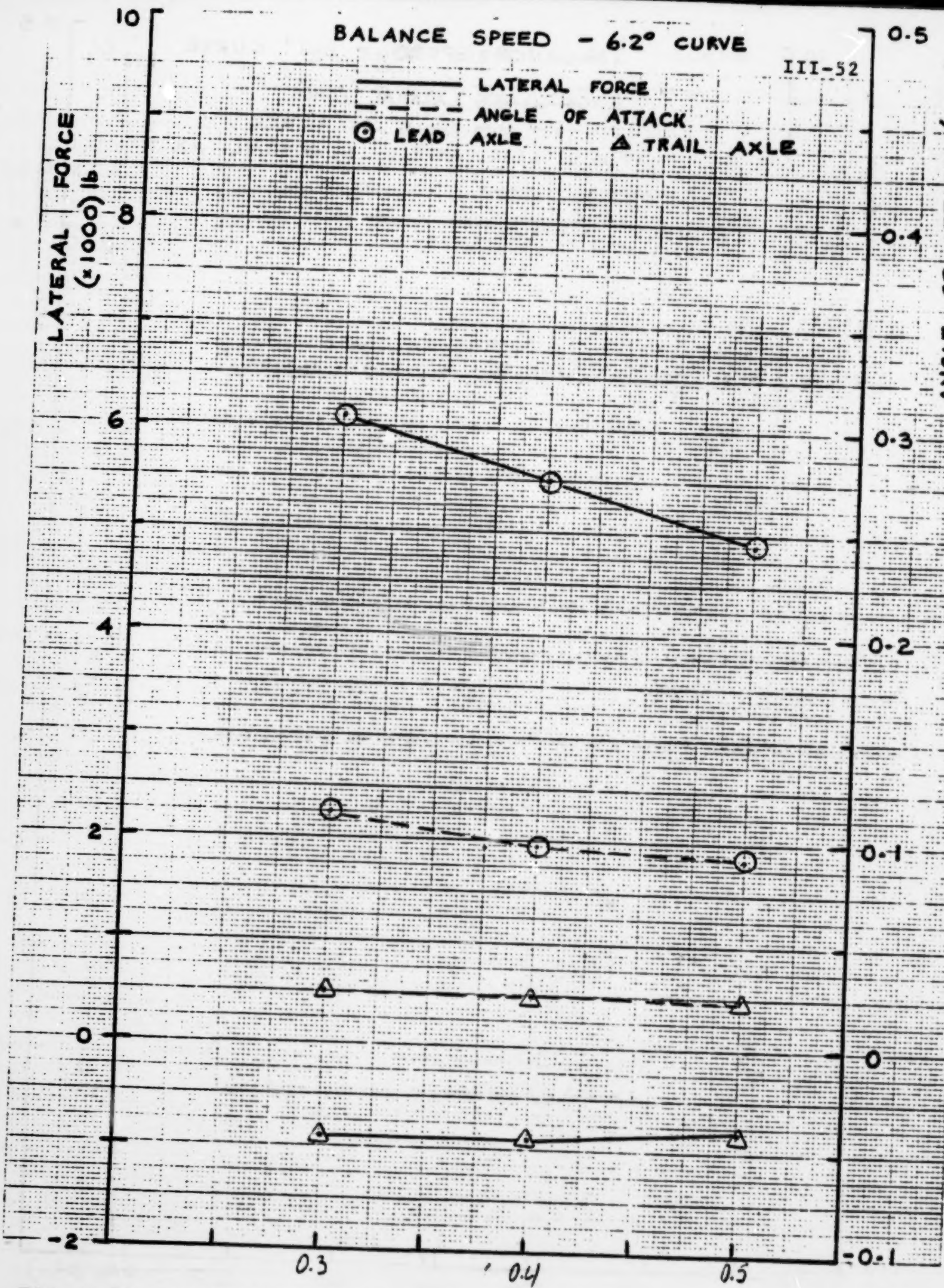

FIG. 5.15 LATERAL FORCE AND ANGLE OF ATTACK VERSUS COEFFICIENT OF FRICTION: DR-1 TRUCK

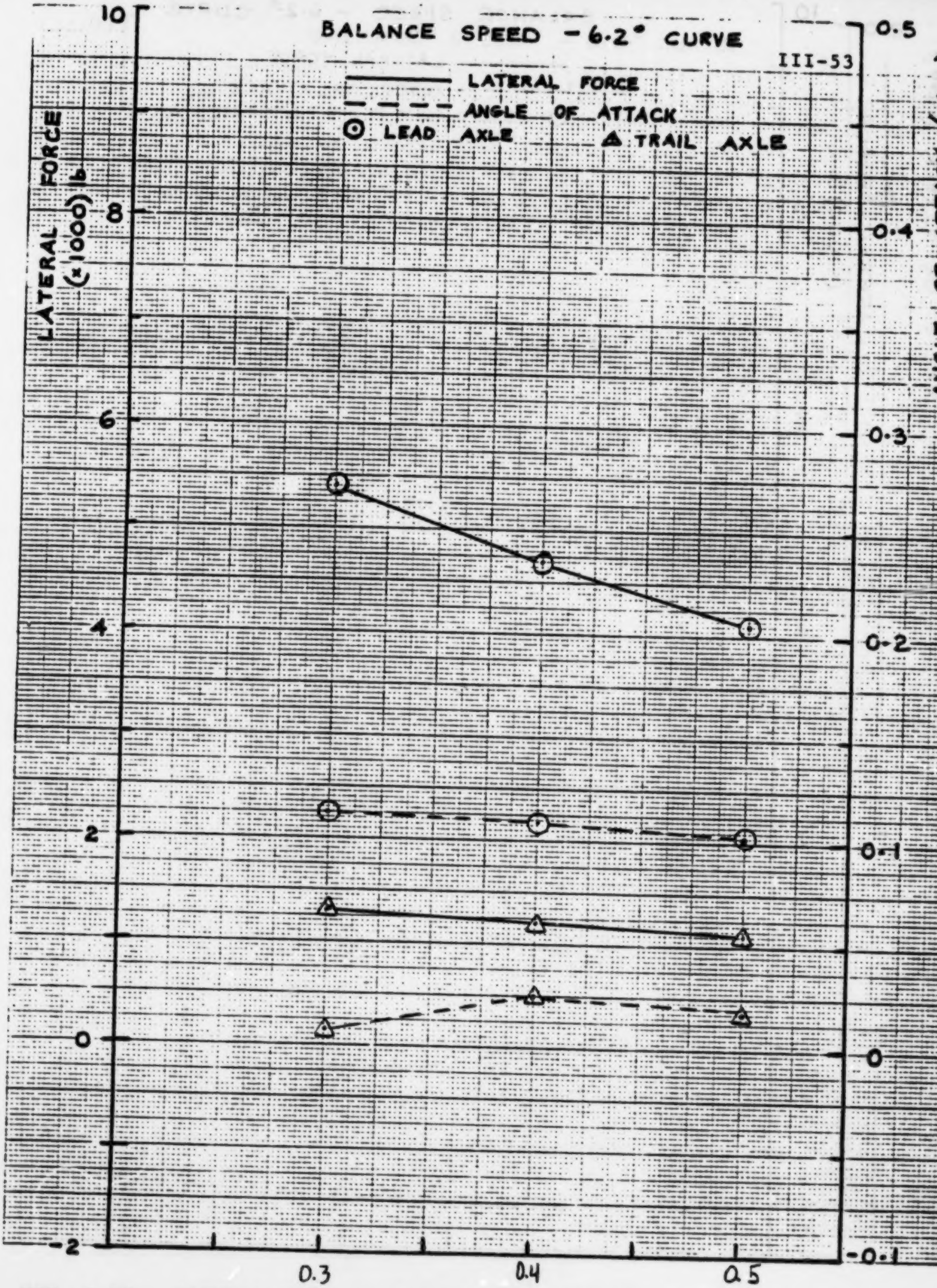

FIG. 5.16 LATERAL FORCE AND ANGLE OF ATTACK VERSUS COEFFICIENT OF FRICTION: BARBER-SCHEFFEL TRUCK

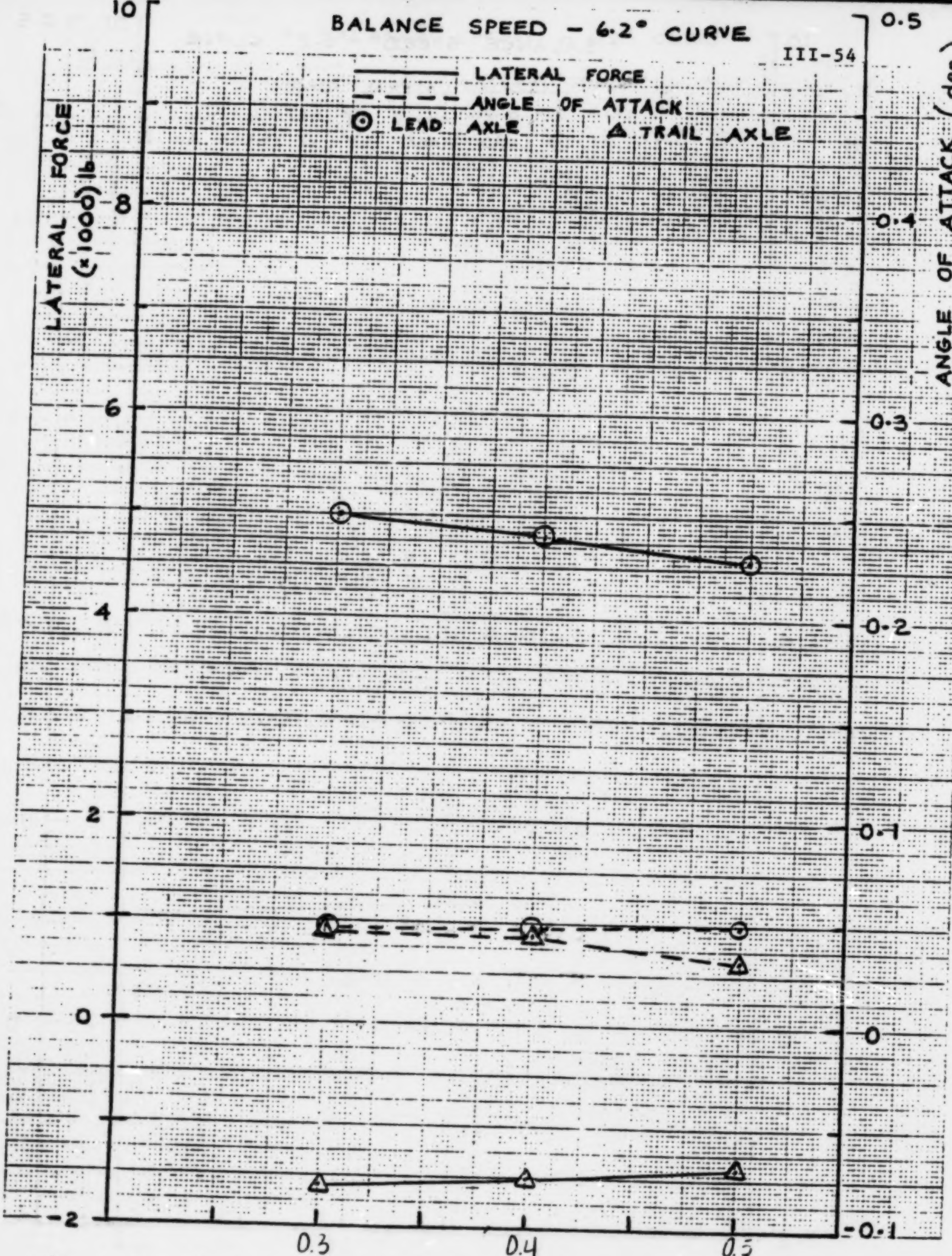

FIG. 5.17 LATERAL FORCE AND ANGLE OF ATTACK VERSUS COEFFICIENT OF FRICTION: DEVINE-SCALES TRUCK

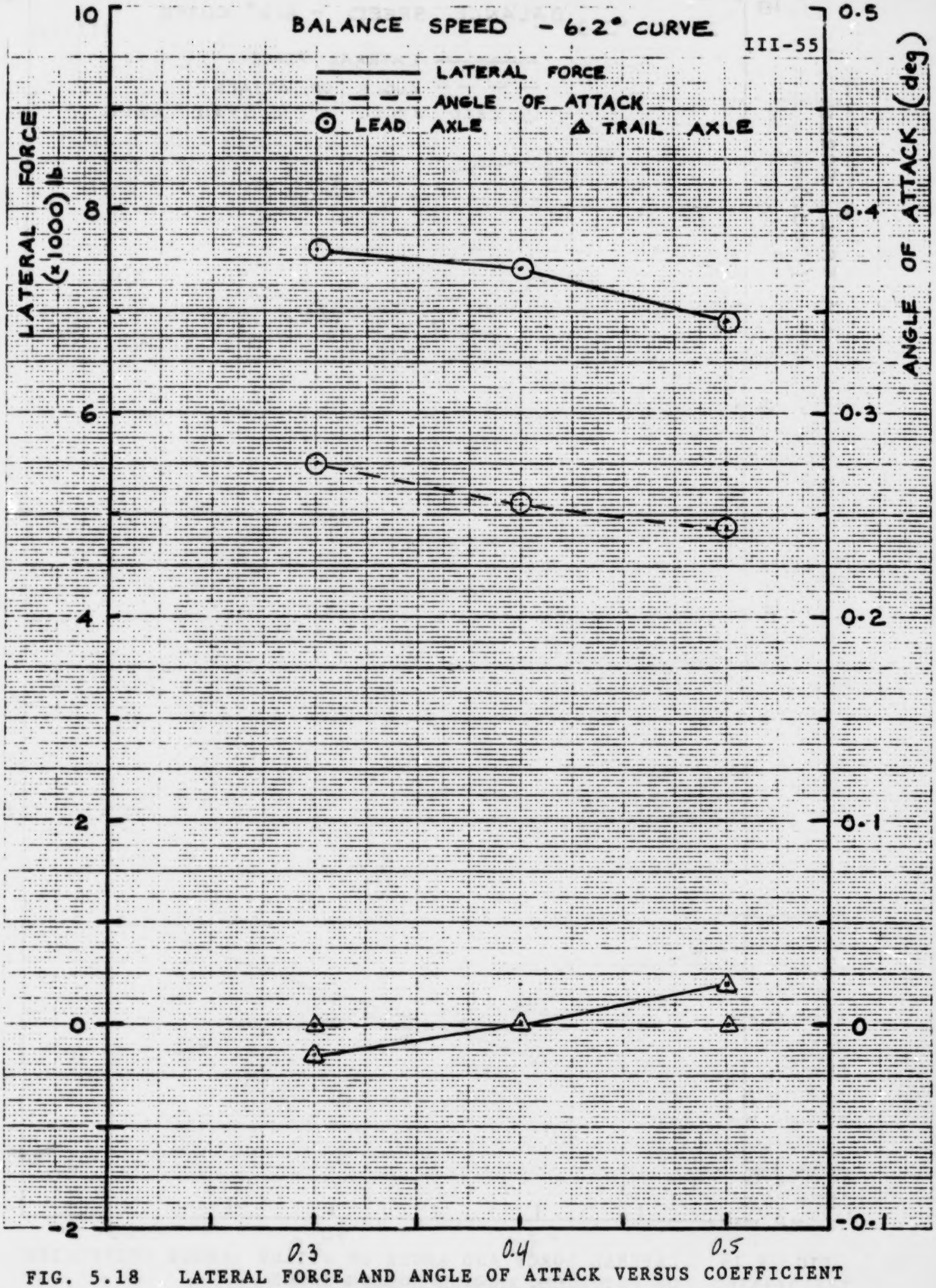

FIG. 5.18 LATERAL FORCE AND ANGLE OF ATTACK VERSUS COEFFICIENT OF FRICTION: MAXIRIDE TRUCK

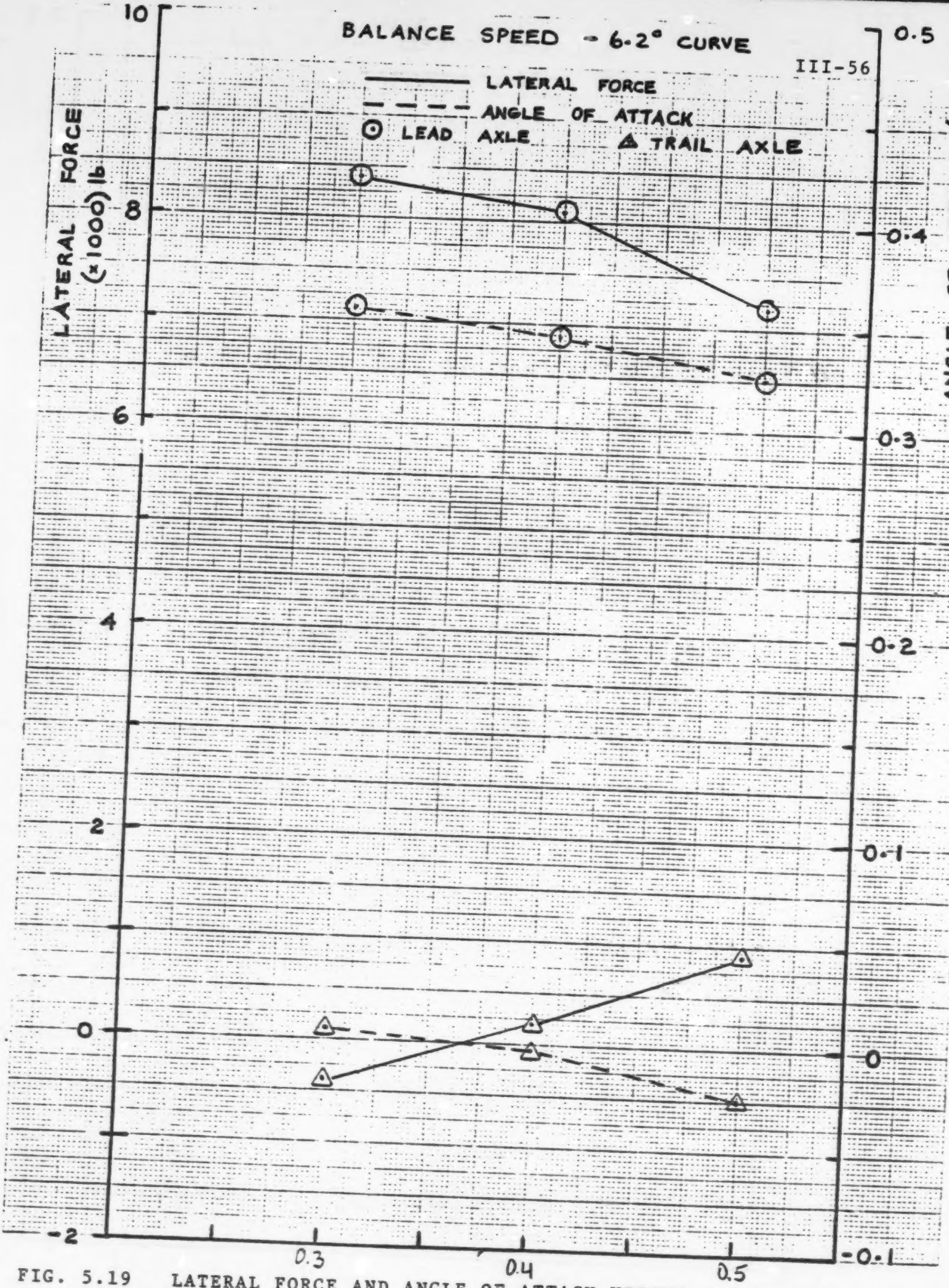

FIG. 5.19 LATERAL FORCE AND ANGLE OF ATTACK VERSUS COEFFICIENT OF FRICTION: SWING MOTION TRUCK

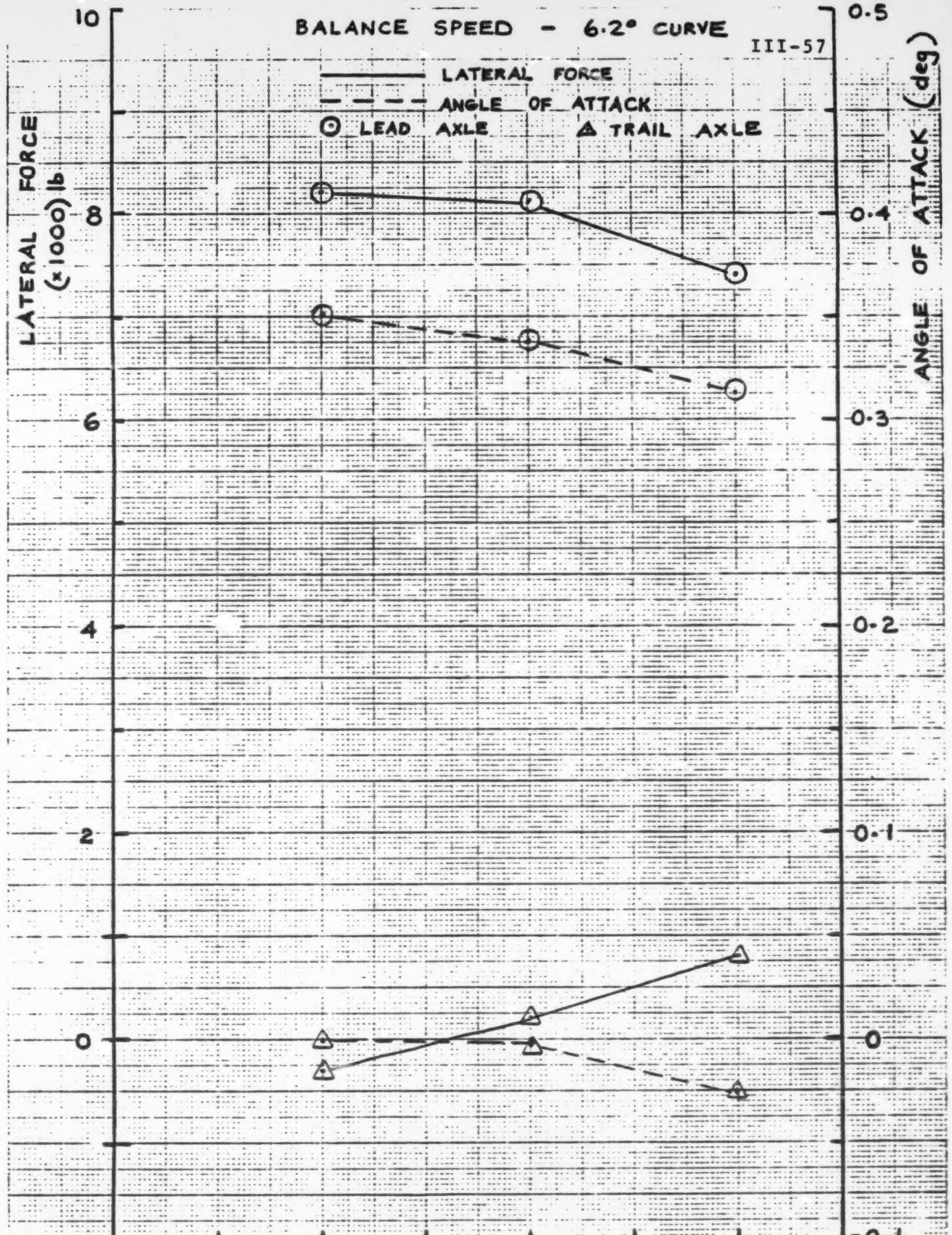

FIG. 5.20 LATERAL FORCE AND ANGLE OF ATTACK VERSUS COEFFICIENT OF FRICTION: ACF FABRICATED TRUCK

6.0 REFERENCES

1. Interim Report - "Type I Truck Steady-State Curving Simulations". DSL Dynamic Sciences Limited, May 1981.
2. P. Marcotte, W.M. Caldwell, H.A. List: "Performance Analysis and Testing of a Conventional Three-Piece Freight Car Truck Retrofitted to Provide Axle Steering" presented at Technical Session, Dynamic Systems and Control Division, ASME Winter Annual Meeting, San Francisco, December 12, 1978.
3. "TDOP Phase II Performance Specification for Type II Trucks - Final Draft", April 2, 1981. Wyle Laboratories, Scientific Services and Systems Group, Colorado Operations.
4. P.P. Marcotte, K.J.R. Mathewson, W.M. Caldwell: "Improved Wheel Tread Profiles for Heavy Freight Vehicles" Transaction of the ASME Journal of Eng. for Industry. August 1980, vol. 102, pp. 263-271.
5. A.H. Collins, C. Pritchard: "Recent Research on Adhesion" Railway Engineering Journal (REJ) September 1972.

APPENDIX A

LISTS OF INPUT PARAMETERS FOR TYPE II TRUCKS (LOADED VEHICLE CONDITION)

```
        RUN W-9-201,    DR-1 LOADED: CN HEUMANN PROFILE
            17-06-81; PF.022 (11/05/81) NO MODS; DSL-3 (11/06/81)
            DEG  2.50    SPEED  48.5    SUPERELEVATION  4.09

       TRUCK CURVING PROGRAM. (11/06/81).
    <<<  2 - AXLE NON-RIGID FRAME TRUCK  >>>
   INPUT PARAMETERS:
 #                 DESCRIPTION:                                   VALUE:

   VEHICLE:
  1         HALF WHEELBASE.                                     243.00000
  2         EQUIV. HEIGHT OF C/G ABOVE RAILHEAD.                 86.04000
  3         HEIGHT OF COUPLER ABOVE RAILHEAD.                    33.00000
   TRUCK:
  4         HALF WHEELBASE.                                      35.00000
  5         TRUCK CENTRE TO BEARINGS (LATERAL).                  39.50000
  6         RAILHEAD TO TRACTION PAD.                             0.00000
  7         RAILHEAD TO AXLE INTERCONNECTION.                    17.00000
   TRACK:
  8         HALF KINEMATIC GAUGE.                                29.75000
  9         RAILHEAD RADIUS.                                     10.00000
 10         SUPERELEVATION DEFICIENCY.                           -0.00643
 11         FLANGE TO TREAD CONTACT (VERTICAL).                   0.28000
   MISC.:
 12         FRICTION COEFF. AT TREAD CONTACT.                     0.30000
 13         FRICTION COEFF. AT FLANGE CONTACT.                    0.30000
 14         HALF TOTAL FLANGE CLEARANCE.                          0.50000
 15         FLANGE TO TREAD CONTACT (LATERAL).                    1.50000
 16         DIMENSIONLESS TRACTIVE EFFORT.                        0.00000
 17         CREEP COEFFICIENT FACTOR.                             0.70000
 18         EXTERNAL LATERAL FORCE PER TRUCK.                     0.00000
   WHEELS:                             (+ = OUT; - = IN).
 19         INITIAL LOAD: HIGH RAIL:  LEAD(L).                29663.00000
 20                                  TRAIL(T).                29663.00000
 21                                 CENTRE(C).                    0.00000
 22                       LOW RAIL:      (L).                 29663.00000
 23                                      (T).                 29663.00000
 24                                      (C).                     0.00000
 25         MEAN RADIUS AT CENTRAL AXLE  (L).                    18.00000
 26                         POSITIONS:   (T).                    18.00000
 27                                      (C).                     0.00000
 28         DIFFERENCE IN RADII:         (L).                     0.00000
 29          (HIGH RAIL - LOW RAIL).     (T).                     0.00000
 30                                      (C).                     0.00000
 31         FLANGE CONTACT PLANE ANGLE. (DEG).                   40.00000
 32         TREAD CONICITY.                                       0.05000
   STIFFNESSES:
 33         FLANGE CONTACT (LATERAL).                       1000000.00000
 34         TRUCK YAW (+ = LEAD; - = TRAIL).                      0.00000
 35         TRUCK/BEARING LATERAL        (L).                   500.00000
 36           WITHIN PEDESTAL CLEARANCE  (T).                   500.00000
 37           (PER AXLE).                (C).                     0.00000
 38         TRUCK/BEARING LONGITUDINAL   (L).                 15000.00000
 39         (PER BEARING) HIGH RAIL SIDE: (T).                15000.00000
 40                                      (C).                     0.00000
 41                     LOW RAIL SIDE:   (L).                 15000.00000
 42                                      (T).                 15000.00000
 43                                      (C).                     0.00000
 44         INTER-AXLE (LATERAL).                             36000.00000
```

```
        AXLE CLEARANCES:
 45             HALF FREE PLAY, AXLE/BEARING. (L).              0.00000
 46                                           (T).              0.00000
 47                                           (C).              0.00000
 48             HALF TOTAL PEDESTAL CLEARANCE (L).              0.92000
 49               (LATERAL).                  (T).              0.92000
 50                                           (C).              0.00000
 51             HALF TOTAL PEDESTAL CLEARANCE (L).              0.25000
 52              (LONGITUDINAL).   (HIGH RAIL)(T).              0.25000
 53                                           (C).              0.00000
 54                                 (LOW RAIL)(L).              0.25000
 55                                           (T).              0.25000
 56                                           (C).              0.00000
        TRAM ERRORS:
 57             LATERAL AXLE ERROR.           (L).              0.00000
 58                                           (T).              0.00000
 59                                           (C).              0.00000
 60             LONGITUDINAL AXLE ERROR.      (L).              0.00000
 61                                           (T).              0.00000
 62                                           (C).              0.00000
 63             YAW AXLE ERROR.               (L).              0.00000
 64                                           (T).              0.00000
 65                                           (C).              0.00000
 66             LATERAL TRUCK ERROR.                            0.00000
 67             YAW TRUCK ERROR.                                0.00000
```

```
        RUN W-9-301,    SHEFFEL LOADED: CN HEUMANN PROFILE
            17-06-81; PF.024 (12/05/81) NO MODS; DSL-3 (11/06/81)
            DEG  2.50     SPEED  48.5    SUPERELEVATION  4.09

       TRUCK CURVING PROGRAM. (11/06/81).
    <<<  2 - AXLE NON-RIGID FRAME TRUCK  >>>
  INPUT PARAMETERS:
 #                   DESCRIPTION:                                  VALUE:
  VEHICLE:
  1        HALF WHEELBASE.                                     243.00000
  2        EQUIV. HEIGHT OF C/G ABOVE RAILHEAD.                 86.04000
  3        HEIGHT OF COUPLER ABOVE RAILHEAD.                    33.00000
  TRUCK:
  4        HALF WHEELBASE.                                      37.50000
  5        TRUCK CENTRE TO BEARINGS (LATERAL).                  39.50000
  6        RAILHEAD TO TRACTION PAD.                             0.00000
  7        RAILHEAD TO AXLE INTERCONNECTION.                    18.00000
  TRACK:
  8        HALF KINEMATIC GAUGE.                                29.75000
  9        RAILHEAD RADIUS.                                     10.00000
 10        SUPERELEVATION DEFICIENCY.                           -0.00643
 11        FLANGE TO TREAD CONTACT (VERTICAL).                   0.28000
  MISC.:
 12        FRICTION COEFF. AT TREAD CONTACT.                     0.30000
 13        FRICTION COEFF. AT FLANGE CONTACT.                    0.30000
 14        HALF TOTAL FLANGE CLEARANCE.                          0.50000
 15        FLANGE TO TREAD CONTACT (LATERAL).                    1.50000
 16        DIMENSIONLESS TRACTIVE EFFORT.                        0.00000
 17        CREEP COEFFICIENT FACTOR.                             0.70000
 18        EXTERNAL LATERAL FORCE PER TRUCK.                     0.00000
  WHEELS:                       (+ = OUT; - = IN).
 19        INITIAL LOAD: HIGH RAIL:  LEAD(L).                29663.00000
 20                                 TRAIL(T).                29663.00000
 21                                CENTRE(C).                    0.00000
 22                      LOW RAIL:      (L).                 29663.00000
 23                                     (T).                 29663.00000
 24                                     (C).                     0.00000
 25        MEAN RADIUS AT CENTRAL AXLE  (L).                    18.00000
 26                        POSITIONS:   (T).                    18.00000
 27                                     (C).                     0.00000
 28        DIFFERENCE IN RADII:         (L).                     0.00000
 29         (HIGH RAIL - LOW RAIL).     (T).                     0.00000
 30                                     (C).                     0.00000
 31        FLANGE CONTACT PLANE ANGLE. (DEG).                   40.00000
 32        TREAD CONICITY.                                       0.05000
  STIFFNESSES:
 33        FLANGE CONTACT (LATERAL).                       1000000.00000
 34        TRUCK YAW (+ = LEAD; - = TRAIL).                      0.00000
 35        TRUCK/BEARING LATERAL        (L).                   500.00000
 36          WITHIN PEDESTAL CLEARANCE  (T).                   500.00000
 37          (PER AXLE).                (C).                     0.00000
 38        TRUCK/BEARING LONGITUDINAL   (L).                  7500.00000
 39        (PER BEARING) HIGH RAIL SIDE: (T).                 7500.00000
 40                                     (C).                     0.00000
 41                      LOW RAIL SIDE: (L).                  7500.00000
 42                                     (T).                  7500.00000
 43                                     (C).                     0.00000
 44        INTER-AXLE (LATERAL).                              9000.00000
```

```
        AXLE CLEARANCES:
  45          HALF FREE PLAY, AXLE/BEARING. (L).                 0.00000
  46                                        (T).                 0.00000
  47                                        (C).                 0.00000
  48          HALF TOTAL PEDESTAL CLEARANCE (L).                 0.92000
  49            (LATERAL).                  (T).                 0.92000
  50                                        (C).                 0.00000
  51          HALF TOTAL PEDESTAL CLEARANCE (L).                 0.91000
  52           (LONGITUDINAL).    (HIGH RAIL)(T).                0.91000
  53                                        (C).                 0.00000
  54                               (LOW RAIL)(L).                0.91000
  55                                        (T).                 0.91000
  56                                        (C).                 0.00000
        TRAM ERRORS:
  57          LATERAL AXLE ERROR.           (L).                 0.00000
  58                                        (T).                 0.00000
  59                                        (C).                 0.00000
  60          LONGITUDINAL AXLE ERROR.      (L).                 0.00000
  61                                        (T).                 0.00000
  62                                        (C).                 0.00000
  63          YAW AXLE ERROR.               (L).                 0.00000
  64                                        (T).                 0.00000
  65                                        (C).                 0.00000
  66          LATERAL TRUCK ERROR.                               0.00000
  67          YAW TRUCK ERROR.                                   0.00000
```

```
                    RUN W-9-401,    SCALES LOADED: CN HEUMANN PROFILE
                        17-06-81; PF.200 (11/06/81) NO MODS; DSL-3 (11/06/81)
                        DEG  2.50     SPEED  48.5    SUPERELEVATION  4.09

                  TRUCK CURVING PROGRAM. (11/06/81).
              <<<  2 - AXLE    SCALES FRAME TRUCK  >>>
           INPUT PARAMETERS:
   #                   DESCRIPTION:                                      VALUE:
           VEHICLE:
    1            HALF WHEELBASE.                                      243.00000
    2            EQUIV. HEIGHT OF C/G ABOVE RAILHEAD.                  86.04000
    3            HEIGHT OF COUPLER ABOVE RAILHEAD.                     33.00000
           TRUCK:
    4            HALF WHEELBASE.                                       35.00000
    5            TRUCK CENTRE TO BEARINGS (LATERAL).                   39.50000
    6            RAILHEAD TO TRACTION PAD.                              0.00000
    7            RAILHEAD TO AXLE INTERCONNECTION.                     17.00000
           TRACK:
    8            HALF KINEMATIC GAUGE.                                 29.75000
    9            RAILHEAD RADIUS.                                      10.00000
   10            SUPERELEVATION DEFICIENCY.                            -0.00643
   11            FLANGE TO TREAD CONTACT (VERTICAL).                    0.28000
           MISC.:
   12            FRICTION COEFF. AT TREAD CONTACT.                      0.30000
   13            FRICTION COEFF. AT FLANGE CONTACT.                     0.30000
   14            HALF TOTAL FLANGE CLEARANCE.                           0.50000
   15            FLANGE TO TREAD CONTACT (LATERAL).                     1.50000
   16            DIMENSIONLESS TRACTIVE EFFORT.                         0.00000
   17            CREEP COEFFICIENT FACTOR.                              0.70000
   18            EXTERNAL LATERAL FORCE PER TRUCK.                      0.00000
           WHEELS:                         (+ = OUT; - = IN).
   19            INITIAL LOAD: HIGH RAIL:  LEAD(L).                 29663.00000
   20                                      TRAIL(T).                29663.00000
   21                                     CENTRE(C).                    0.00000
   22                         LOW RAIL:         (L).                29663.00000
   23                                           (T).                29663.00000
   24                                           (C).                    0.00000
   25          MEAN RADIUS AT CENTRAL AXLE      (L).                   18.00000
   26                           POSITIONS:      (T).                   18.00000
   27                                           (C).                    0.00000
   28          DIFFERENCE IN RADII:             (L).                    0.00000
   29           (HIGH RAIL - LOW RAIL).         (T).                    0.00000
   30                                           (C).                    0.00000
   31          FLANGE CONTACT PLANE ANGLE. (DEG).                      40.00000
   32          TREAD CONICITY.                                          0.05000
          STIFFNESSES:
   33          FLANGE CONTACT (LATERAL).                          1000000.00000
   34          TRUCK YAW (+ = LEAD; - = TRAIL).                         0.00000
   35          TRUCK/BEARING LATERAL            (L).               200000.00000
   36            WITHIN PEDESTAL CLEARANCE      (T).               200000.00000
   37            (PER AXLE).                    (C).                    0.00000
   38          TRUCK/BEARING LONGITUDINAL       (L).                 1000.00000
   39          (PER BEARING) HIGH RAIL SIDE:    (T).                 1000.00000
   40                                           (C).                    0.00000
   41                          LOW RAIL SIDE:   (L).                 1000.00000
   42                                           (T).                 1000.00000
   43                                           (C).                    0.00000
   44          INTER-AXLE (LATERAL).                                    0.00000
```

```
     AXLE CLEARANCES:
 45          HALF FREE PLAY, AXLE/BEARING. (L).             0.00000
 46                                        (T).             0.00000
 47                                        (C).             0.00000
 48          HALF TOTAL PEDESTAL CLEARANCE (L).             1.00000
 49            (LATERAL).                  (T).             1.00000
 50                                        (C).             0.00000
 51          HALF TOTAL PEDESTAL CLEARANCE (L).            10.00000
 52           (LONGITUDINAL).   (HIGH RAIL)(T).            10.00000
 53                                        (C).             0.00000
 54                              (LOW RAIL)(L).            10.00000
 55                                        (T).            10.00000
 56                                        (C).             0.00000
     TRAM ERRORS:
 57          LATERAL AXLE ERROR.           (L).             0.00000
 58                                        (T).             0.00000
 59                                        (C).             0.00000
 60          LONGITUDINAL AXLE ERROR.      (L).             0.00000
 61                                        (T).             0.00000
 62                                        (C).             0.00000
 63          YAW AXLE ERROR.               (L).             0.00000
 64                                        (T).             0.00000
 65                                        (C).             0.00000
 66          LATERAL TRUCK ERROR.                           0.00000
 67          YAW TRUCK ERROR.                               0.00000
     SCALES TRUCK:
 68          TRAM ERROR: BODY YAW.                          0.00000
 69          AXLE STEERING LINK STIFFNESS.             200000.00000
 70          BODY STEERING LINK STIFFNESS.              50000.00000
 71          TRUCK CENTRELINE TO FRAME PIVOT.              39.50000
 72          TRUCK CENTRELINE TO BODY LINK.                57.00000
 73          LENGTH: AXLE LINK TO FRAME PIVOT.              1.74700
```

```
           RUN W-9-501,    MAXIRIDE LOADED: CN HEUMANN PROFILE
               17-06-81; PF.028 (12/05/81) NO MODS; DSL-3 (11/06/81)
               DEG  2.50    SPEED  48.5    SUPERELEVATION  4.09

          TRUCK CURVING PROGRAM. (11/06/81).
        <<<  2 - AXLE     RIGID FRAME TRUCK   >>>
      INPUT PARAMETERS:
  #                   DESCRIPTION:                                 VALUE:

      VEHICLE:
  1          HALF WHEELBASE.                                     243.00000
  2          EQUIV. HEIGHT OF C/G ABOVE RAILHEAD.                 86.04000
  3          HEIGHT OF COUPLER ABOVE RAILHEAD.                    33.00000
      TRUCK:
  4          HALF WHEELBASE.                                      36.22000
  5          TRUCK CENTRE TO BEARINGS (LATERAL).                  39.50000
  6          RAILHEAD TO TRACTION PAD.                             0.00000
  7          RAILHEAD TO AXLE INTERCONNECTION.                     0.00000
      TRACK:
  8          HALF KINEMATIC GAUGE.                                29.75000
  9          RAILHEAD RADIUS.                                     10.00000
 10          SUPERELEVATION DEFICIENCY.                           -0.00643
 11          FLANGE TO TREAD CONTACT (VERTICAL).                   0.28000
      MISC.:
 12          FRICTION COEFF. AT TREAD CONTACT.                     0.30000
 13          FRICTION COEFF. AT FLANGE CONTACT.                    0.30000
 14          HALF TOTAL FLANGE CLEARANCE.                          0.50000
 15          FLANGE TO TREAD CONTACT (LATERAL).                    1.50000
 16          DIMENSIONLESS TRACTIVE EFFORT.                        0.00000
 17          CREEP COEFFICIENT FACTOR.                             0.70000
 18          EXTERNAL LATERAL FORCE PER TRUCK.                     0.00000
      WHEELS:                          (+ = OUT; - = IN).
 19          INITIAL LOAD: HIGH RAIL:  LEAD(L).                29663.00000
 20                                   TRAIL(T).                29663.00000
 21                                  CENTRE(C).                    0.00000
 22                        LOW RAIL:       (L).                29663.00000
 23                                        (T).                29663.00000
 24                                        (C).                    0.00000
 25          MEAN RADIUS AT CENTRAL AXLE   (L).                   18.00000
 26                          POSITIONS:    (T).                   18.00000
 27                                        (C).                    0.00000
 28          DIFFERENCE IN RADII:          (L).                    0.00000
 29           (HIGH RAIL - LOW RAIL).      (T).                    0.00000
 30                                        (C).                    0.00000
 31          FLANGE CONTACT PLANE ANGLE. (DEG).                   40.00000
 32          TREAD CONICITY.                                       0.05000
      STIFFNESSES:
 33          FLANGE CONTACT (LATERAL).                      1000000.00000
 34          TRUCK YAW (+ = LEAD; - = TRAIL).                      0.00000
 35          TRUCK/BEARING LATERAL            (L).             14000.00000
 36            WITHIN PEDESTAL CLEARANCE      (T).             14000.00000
 37            (PER AXLE).                    (C).                 0.00000
 38          TRUCK/BEARING LONGITUDINAL       (L).              7000.00000
 39          (PER BEARING) HIGH RAIL SIDE:    (T).              7000.00000
 40                                           (C).                 0.00000
 41                         LOW RAIL SIDE:    (L).              7000.00000
 42                                           (T).              7000.00000
 43                                           (C).                 0.00000
 44          INTER-AXLE (LATERAL).                                 0.00000
```

```
       AXLE CLEARANCES:
45           HALF FREE PLAY, AXLE/BEARING. (L).                0.00000
46                                         (T).                0.00000
47                                         (C).                0.00000
48           HALF TOTAL PEDESTAL CLEARANCE (L).                0.50000
49             (LATERAL).                  (T).                0.50000
50                                         (C).                0.00000
51           HALF TOTAL PEDESTAL CLEARANCE (L).                0.03300
52            (LONGITUDINAL).   (HIGH RAIL)(T).                0.03300
53                                         (C).                0.00000
54                               (LOW RAIL)(L).                0.03300
55                                         (T).                0.03300
56                                         (C).                0.00000
       TRAM ERRORS:
57           LATERAL AXLE ERROR.           (L).                0.00000
58                                         (T).                0.00000
59                                         (C).                0.00000
60           LONGITUDINAL AXLE ERROR.      (L).                0.00000
61                                         (T).                0.00000
62                                         (C).                0.00000
63           YAW AXLE ERROR.               (L).                0.00000
64                                         (T).                0.00000
65                                         (C).                0.00000
66           LATERAL TRUCK ERROR.                              0.00000
67           YAW TRUCK ERROR.                                  0.00000
```

```
          RUN W-9-601,    SWG MTN LOADED: CN HEUMANN PROFILE
              17-06-81; PF.026 (12/05/81) NO MODS; DSL-3 (11/06/81)
              DEG  2.50     SPEED  48.5    SUPERELEVATION  4.09

        TRUCK CURVING PROGRAM. (11/06/81).
     <<<  2 - AXLE NON-RIGID FRAME TRUCK  >>>
   INPUT PARAMETERS:
 #                  DESCRIPTION:                                    VALUE:

   VEHICLE:
 1          HALF WHEELBASE.                                     243.00000
 2          EQUIV. HEIGHT OF C/G ABOVE RAILHEAD.                 86.04000
 3          HEIGHT OF COUPLER ABOVE RAILHEAD.                    33.00000
   TRUCK:
 4          HALF WHEELBASE.                                      36.00000
 5          TRUCK CENTRE TO BEARINGS (LATERAL).                  39.50000
 6          RAILHEAD TO TRACTION PAD.                             0.00000
 7          RAILHEAD TO AXLE INTERCONNECTION.                     0.00000
   TRACK:
 8          HALF KINEMATIC GAUGE.                                29.75000
 9          RAILHEAD RADIUS.                                     10.00000
10          SUPERELEVATION DEFICIENCY.                           -0.00643
11          FLANGE TO TREAD CONTACT (VERTICAL).                   0.28000
   MISC.:
12          FRICTION COEFF. AT TREAD CONTACT.                     0.30000
13          FRICTION COEFF. AT FLANGE CONTACT.                    0.30000
14          HALF TOTAL FLANGE CLEARANCE.                          0.50000
15          FLANGE TO TREAD CONTACT (LATERAL).                    1.50000
16          DIMENSIONLESS TRACTIVE EFFORT.                        0.00000
17          CREEP COEFFICIENT FACTOR.                             0.70000
18          EXTERNAL LATERAL FORCE PER TRUCK.                     0.00000
   WHEELS:                              (+ = OUT; - = IN).
19          INITIAL LOAD: HIGH RAIL:  LEAD(L).                29663.00000
20                                   TRAIL(T).                29663.00000
21                                  CENTRE(C).                    0.00000
22                       LOW RAIL:        (L).                29663.00000
23                                        (T).                29663.00000
24                                        (C).                    0.00000
25          MEAN RADIUS AT CENTRAL AXLE   (L).                   18.00000
26                           POSITIONS:   (T).                   18.00000
27                                        (C).                    0.00000
28          DIFFERENCE IN RADII:          (L).                    0.00000
29           (HIGH RAIL - LOW RAIL).      (T).                    0.00000
30                                        (C).                    0.00000
31          FLANGE CONTACT PLANE ANGLE. (DEG).                   40.00000
32          TREAD CONICITY.                                       0.05000
   STIFFNESSES:
33          FLANGE CONTACT (LATERAL).                       1000000.00000
34          TRUCK YAW (+ = LEAD; - = TRAIL).                      0.00000
35          TRUCK/BEARING LATERAL         (L).               500000.00000
36            WITHIN PEDESTAL CLEARANCE   (T).               500000.00000
37            (PER AXLE).                 (C).                    0.00000
38          TRUCK/BEARING LONGITUDINAL    (L).               500000.00000
39          (PER BEARING) HIGH RAIL SIDE: (T).               500000.00000
40                                        (C).                    0.00000
41                        LOW RAIL SIDE:  (L).               500000.00000
42                                        (T).               500000.00000
43                                        (C).                    0.00000
44          INTER-AXLE (LATERAL).                                 0.00000
```

```
       AXLE CLEARANCES:
 45          HALF FREE PLAY, AXLE/BEARING. (L).              0.00000
 46                                        (T).              0.00000
 47                                        (C).              0.00000
 48          HALF TOTAL PEDESTAL CLEARANCE (L).              0.92000
 49            (LATERAL).                  (T).              0.92000
 50                                        (C).              0.00000
 51          HALF TOTAL PEDESTAL CLEARANCE (L).            100.00000
 52           (LONGITUDINAL).   (HIGH RAIL)(T).            100.00000
 53                                        (C).              0.00000
 54                              (LOW RAIL)(L).            100.00000
 55                                        (T).            100.00000
 56                                        (C).              0.00000
       TRAM ERRORS:
 57          LATERAL AXLE ERROR.           (L).              0.00000
 58                                        (T).              0.00000
 59                                        (C).              0.00000
 60          LONGITUDINAL AXLE ERROR.      (L).              0.00000
 61                                        (T).              0.00000
 62                                        (C).              0.00000
 63          YAW AXLE ERROR.               (L).              0.00000
 64                                        (T).              0.00000
 65                                        (C).              0.00000
 66          LATERAL TRUCK ERROR.                            0.00000
 67          YAW TRUCK ERROR.                                0.00000
```

```
           RUN W-9-701,    ACF LOADED: CN HEUMANN PROFILE
                17-06-81; PF.030 (12/05/81) NO MODS; DSL-3 (11/06/81)
                DEG  2.50    SPEED  48.5    SUPERELEVATION  4.09

          TRUCK CURVING PROGRAM. (11/06/81).
       <<<  2 - AXLE NON-RIGID FRAME TRUCK  >>>
     INPUT PARAMETERS:
   #                 DESCRIPTION:
                                                              VALUE:
     VEHICLE:
    1          HALF WHEELBASE.                                   243.00000
    2          EQUIV. HEIGHT OF C/G ABOVE RAILHEAD.               86.04000
    3          HEIGHT OF COUPLER ABOVE RAILHEAD.                  33.00000
     TRUCK:
    4          HALF WHEELBASE.                                    35.00000
    5          TRUCK CENTRE TO BEARINGS (LATERAL).                39.50000
    6          RAILHEAD TO TRACTION PAD.                           0.00000
    7          RAILHEAD TO AXLE INTERCONNECTION.                   0.00000
     TRACK:
    8          HALF KINEMATIC GAUGE.                              29.75000
    9          RAILHEAD RADIUS.                                   10.00000
   10          SUPERELEVATION DEFICIENCY.                         -0.00643
   11          FLANGE TO TREAD CONTACT (VERTICAL).                 0.28000
     MISC.:
   12          FRICTION COEFF. AT TREAD CONTACT.                   0.30000
   13          FRICTION COEFF. AT FLANGE CONTACT.                  0.30000
   14          HALF TOTAL FLANGE CLEARANCE.                        0.50000
   15          FLANGE TO TREAD CONTACT (LATERAL).                  1.50000
   16          DIMENSIONLESS TRACTIVE EFFORT.                      0.00000
   17          CREEP COEFFICIENT FACTOR.                           0.70000
   18          EXTERNAL LATERAL FORCE PER TRUCK.                   0.00000
     WHEELS:                            (+ = OUT; - = IN).
   19          INITIAL LOAD: HIGH RAIL:  LEAD(L).              29663.00000
   20                                   TRAIL(T).              29663.00000
   21                                  CENTRE(C).                  0.00000
   22                        LOW RAIL:       (L).              29663.00000
   23                                        (T).              29663.00000
   24                                        (C).                  0.00000
   25          MEAN RADIUS AT CENTRAL AXLE   (L).                 18.00000
   26                           POSITIONS:   (T).                 18.00000
   27                                        (C).                  0.00000
   28          DIFFERENCE IN RADII:          (L).                  0.00000
   29           (HIGH RAIL - LOW RAIL).      (T).                  0.00000
   30                                        (C).                  0.00000
   31          FLANGE CONTACT PLANE ANGLE. (DEG).                 40.00000
   32          TREAD CONICITY.                                     0.05000
     STIFFNESSES:
   33          FLANGE CONTACT (LATERAL).                     1000000.00000
   34          TRUCK YAW (+ = LEAD; - = TRAIL).                    0.00000
   35          TRUCK/BEARING LATERAL          (L).             30000.00000
   36            WITHIN PEDESTAL CLEARANCE    (T).             30000.00000
   37            (PER AXLE).                  (C).                 0.00000
   38          TRUCK/BEARING LONGITUDINAL     (L).            500000.00000
   39          (PER BEARING) HIGH RAIL SIDE:  (T).            500000.00000
   40                                         (C).                 0.00000
   41                          LOW RAIL SIDE: (L).            500000.00000
   42                                         (T).            500000.00000
   43                                         (C).                 0.00000
   44          INTER-AXLE (LATERAL).                               0.00000
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     AXLE CLEARANCES:
45          HALF FREE PLAY, AXLE/BEARING.  (L).           0.00000
46                                         (T).           0.00000
47                                         (C).           0.00000
48          HALF TOTAL PEDESTAL CLEARANCE  (L).          10.00000
49            (LATERAL).                   (T).          10.00000
50                                         (C).           0.00000
51          HALF TOTAL PEDESTAL CLEARANCE  (L).         100.00000
52           (LONGITUDINAL).    (HIGH RAIL)(T).         100.00000
53                                         (C).           0.00000
54                               (LOW RAIL)(L).         100.00000
55                                         (T).         100.00000
56                                         (C).           0.00000
     TRAM ERRORS:
57          LATERAL AXLE ERROR.            (L).           0.00000
58                                         (T).           0.00000
59                                         (C).           0.00000
60          LONGITUDINAL AXLE ERROR.       (L).           0.00000
61                                         (T).           0.00000
62                                         (C).           0.00000
63          YAW AXLE ERROR.                (L).           0.00000
64                                         (T).           0.00000
65                                         (C).           0.00000
66          LATERAL TRUCK ERROR.                          0.00000
67          YAW TRUCK ERROR.                              0.00000
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